AD-753 327

GAS-PRESSURE BONDING OF MULTILAYER GUN BARRELS

Roy E. Beal, et al

IIT Research Institute

Prepared for:

Army Weapons Command

July 1972

AD753327

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SWERR-TR-72-12

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TECHNICAL REPORT

July 1972

RESEARCH DIRECTORATE

WEAPONS LABORATORY AT ROCK ISLAND

RESEARCH, DEVELOPMENT AND ENGINEERING DIRECTORATE

U. S. ARMY WEAPONS COMMAND

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) IIT Research Institute 10 West 34th Street Chicago, Illinois 60616	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3 REPORT TITLE

GAS-PRESSURE BONDING OF MULTILAYER GUN BARRELS (U)

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

5 AUTHOR(S) (First name, middle initial, last name)

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Thomas Watmough

6 REPORT DATE	7a. TOTAL NO OF PAGES	7b. NO. OF REFS
July 1972	~~50~~ 55	0

8a. CONTRACT OR GRANT NO. DAAF01-71-C-0021 b. PROJECT NO c. AMS Code 4932.06.7017 d.	9a. ORIGINATOR'S REPORT NUMBER(S) IITRI-B6108-4 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) SWERR-TR-72-42

10 DISTRIBUTION STATEMENT

Approved for public release, distribution unlimited.

11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY
	U. S. Army Weapons Command Research & Engineering Directorate Rock Island, Illinois 61201

13 ABSTRACT

A program was undertaken by the Research Directorate, Weapons Laboratory at Rock Island, to determine the feasibility of using gas pressure techniques for production of lined, prerifled gun barrels. Pressure containers constructed from short-length tubular steel sections machined to gun barrel bore dimensions were used in this experiment. From the results of the tests performed with low-yield strength materials (copper and Monel), a suitable profile replication was not attained on the rifle surface. On the basis of test data obtained, forming a rifling profile and bonding with a tantalum alloy on AISI 4130 steel were found to be impractical with gas pressure bonding techniques. (U) (Beal, R. E. and Watmough, T.)

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DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

Unclassified

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Joining						
2. Welding						
3. Solid-state Bonding						
4. Isostatic (Hot) Pressure Bonding						
5. Diffusion Bonding						

Unclassified

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A program was undertaken by the Research Directorate, Weapons Laboratory at Rock Island, to determine the feasibility of using gas pressure techniques for production of lined, prerifled gun barrels. Pressure containers constructed from short-length tubular steel sections machined to gun barrel bore dimensions were used in this experiment. From the results of the tests performed with low-yield strength materials (copper and Monel), a suitable profile replication was not attained on the rifle surface. On the basis of test data obtained, forming a rifling profile and bonding with a tantalum alloy on AISI 4130 steel were found to be impractical with gas pressure bonding techniques.

FOREWORD

This report was prepared by R. B. Beal, J. Dolega, E. Chester, and T. Watmough of the I.I.T. Research Institute, Chicago, Illinois, in compliance with Contract DAAF01-71-C-0021 under the technical supervision of the Research Directorate, Weapons Laboratory at Rock Island, U. S. Army Weapons Command, with R. B. Miclot as project engineer.

The work was authorized as part of the Manufacturing Methods and Technology Program of the U. S. Army Materiel Command which is administered by the U. S. Army Production Equipment Agency.

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1. INTRODUCTION

A rapid-fire weapon generates tremendous quantities of heat, and the high velocity of projectiles and propellant debris moving through the barrel cause rapid erosion of the bore. High strength low alloy steels used in gun barrel manufacture do not offer adequate erosion resistance. A suitable method by which to overcome the erosion problems of alloy steels is that of lining the bore with an erosion resistant material. The liner material must be capable of integral bonding with the barrel to produce a composite material.

A coextrusion method has been developed by the Research Directorate with a refractory alloy liner bonded during the coextrusion process. Although the coextrusion method is satisfactory for bonding refractory alloy liners to steel gun tubes, the subsequent swaging operation can only impart constant twist rifling to the lined tubes. The lining of gain twist rifled gun barrels is a problem area that must be resolved. Explosive forming techniques have been previously used for this lamination process, but the efforts have been unsuccessful.

The possibility of producing a prerifled steel gun barrel to which a suitable liner is subsequently attached has been considered. Two main criteria are involved in the successful application of this approach: first, the reproducing of prerifled profile on the inner surface of the attached liner and, secondly, satisfactory bonding of the liner to the barrel. In this program, the feasibility has been explored with respect to reproducing, on the liner, the prerifled profile machined into the barrel.

With short length tubular sections of SAE 4130 steel, lined sections have been produced at temperatures up to 1000°F with a gas pressure bonding technique. In this approach, the need of a specially designed pressure vessel with internal heating facilities was avoided, and the feasibility of the technique was studied in a relatively inexpensive manner. Three different liner materials were included in the program that made possible an examination of several yield strengths and their influence on liner application without the use of unduly high test temperatures. Less importance was placed on bonding parameters.

The objective of this program was to produce a gain twist rifled gun barrel with a refractory alloy liner for superior erosion resistance. The barrel material must be capable of withstanding high temperature loading; therefore, a design requirement of 40,000 psi yield strength at 1500°F has been stipulated. The liner material is selected from previous erosion work and is the tantalum alloy Ta-10W. This material has a yield strength of 90,000 psi at 1600°F. The outer element or gun barrel will be prerifled. The liner must be attached and take the shape of the barrel. A rifling projection 3/16-inch-wide and 0.005-inch high was required by design. The lining attachment process or method must provide for an efficient metallurgical bond between the liner and the barrel or, at least, facilitate subsequent bonding without destruction of the profile integrity. Also the new processing method should result in some cost savings in production.

2 MATERIALS AND PROCESSES

With this gas-pressure bonding process, a gas at high pressure and elevated temperature is used to fabricate metallic or ceramic materials. The process has been used to promote bonds between similar and dissimilar metals, ceramics, and cermet materials. Advantages include the capacity to fabricate brittle materials and materials of widely differing properties. Gas-pressure bonding also offers uniform chemical, physical, and mechanical properties without cast structures incurred with normal fusion welding processes. Thus, gas bonding could possibly meet the stringent requirements of the metallurgical and joining technique for gun barrels provided the geometric factors are satisfied.

In the gas-pressure bonding process, the components to be bonded are fabricated or machined to final size, cleaned, and assembled into an expendable container or edge-welded to produce a pressure-tight evacuated envelope. The assembled components are heated to an elevated temperature in an autoclave containing an inert gas at a high pressure. The isostatic pressure is uniformly transmitted, and all mating surfaces are forced into contact along the desired surface contour. The mating surfaces are held under pressure at temperature for a sufficient length of time to permit solid-state bonding between the components. The only deformation occurring is that necessary to bring the parts into contact. Strong metallurgical bonds can be produced, and original bond interfaces can be eliminated in compatible metal systems.

Cold-wall resistance-heated autoclaves operating at very high pressures, with test limits indicated by vessel design and furnace requirements, have been developed. For this program, however, a short-length tubular section of steel was considered the most economical pressure container.

Bonds are actually produced by solid-state diffusion through coalescence or welding contacting surfaces and are usually performed near the bulk yield strength and 0.4 of the absolute melting temperature (T_m) of the material. Substantial process temperature reductions are possible by use of a relatively new concept of reaction layer diffusion bonding in which an interlayer of low-melting material is allowed to become liquid and, subsequently to diffuse into the matrices of the materials to be joined. Material compatibility is necessary in both adaptations of the process. No attempts at bond examination or parameter optimization were made in this study. Effort was focused entirely on the reproduction of the rifled profile.

2.1 Manufacture of Short-Length Tubular Sections

2.1.1 Gun Barrel Material

Alloy steel SAE 4130 was selected as the outer element material since the properties of this material at room and elevated temperatures meet the required design criteria. Tests in the program were performed up to 1000°F. SAE 4130 is relatively weldable so that pressure vessels may be fabricated from it. The material was purchased in the normalized and tempered condition.

2.1.2 Fabrication of Pressure Capsules

The outer element was designed as a pressure vessel in accordance with ASME Code Section VIII. A nominal bore dimension of 1-inch diameter and a pressure capacity of 10,000 psi at 1000°F were required. The vessel was also designed to accommodate approximately a 3-inch length of liner for tests. Dimensions of the vessels are given in Figure 1, with details of the pressure entry point and positions of the rifled projections.

The alloy steel SAE 4130 was drilled and broached, as shown in Figure 2 A special broach was manufactured to accurately produce the required rifled surface. Four projection angles of 90 , 75°, 60°, and 45° were broached. Weld preparations were subsequently machined on all specimens and end caps produced.

One pressure-capsule end cap with a gas entry port in the center is shown in Figure 3. A machined and broached section is shown in Figure 4. Barrel thickness is 1-inch, and two broached projections can be seen on the internal surface. A completely machined pressure vessel ready for the main welding operation is shown in Figure 5.

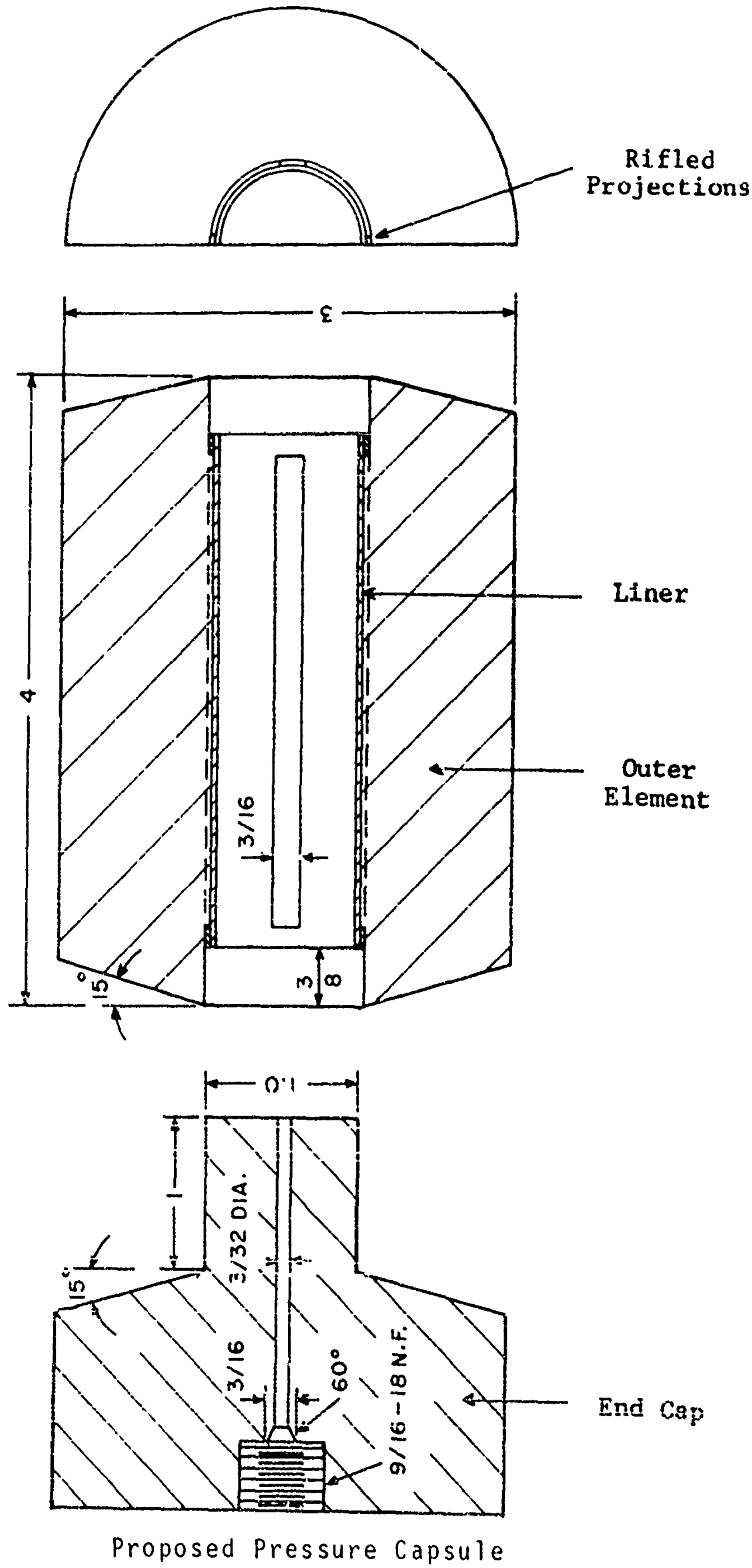


FIGURE 1 Proposed Pressure Capsule

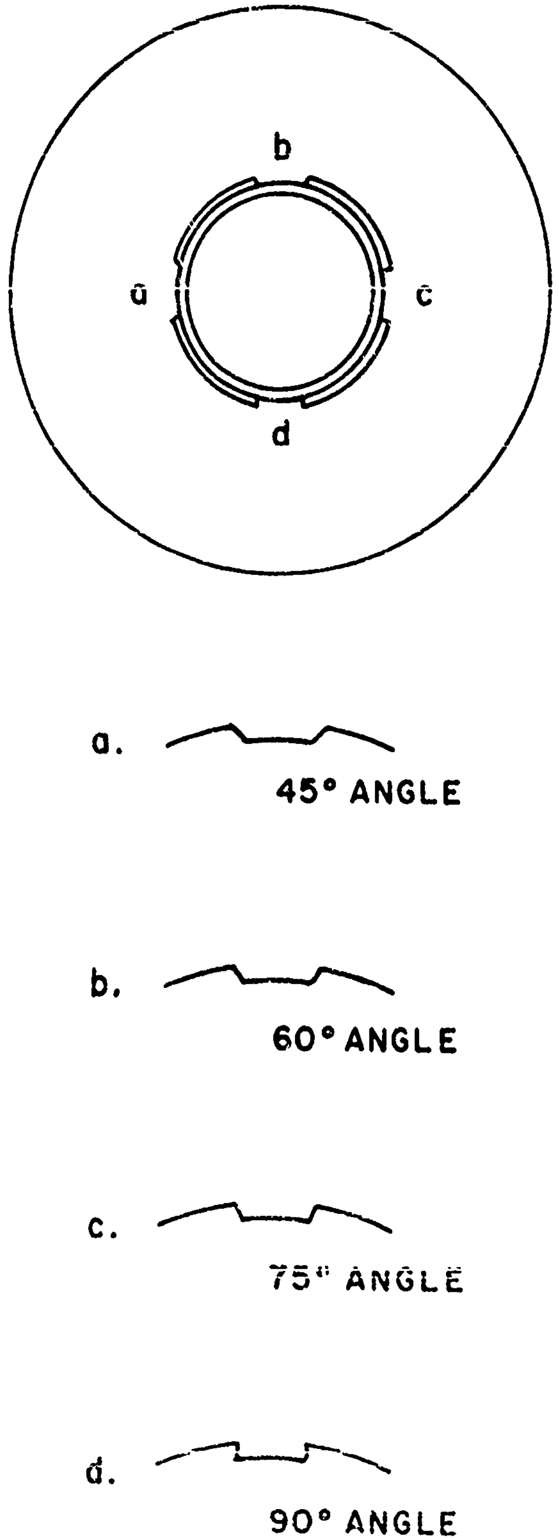


FIGURE 2 Angles Used on Rifled Projections

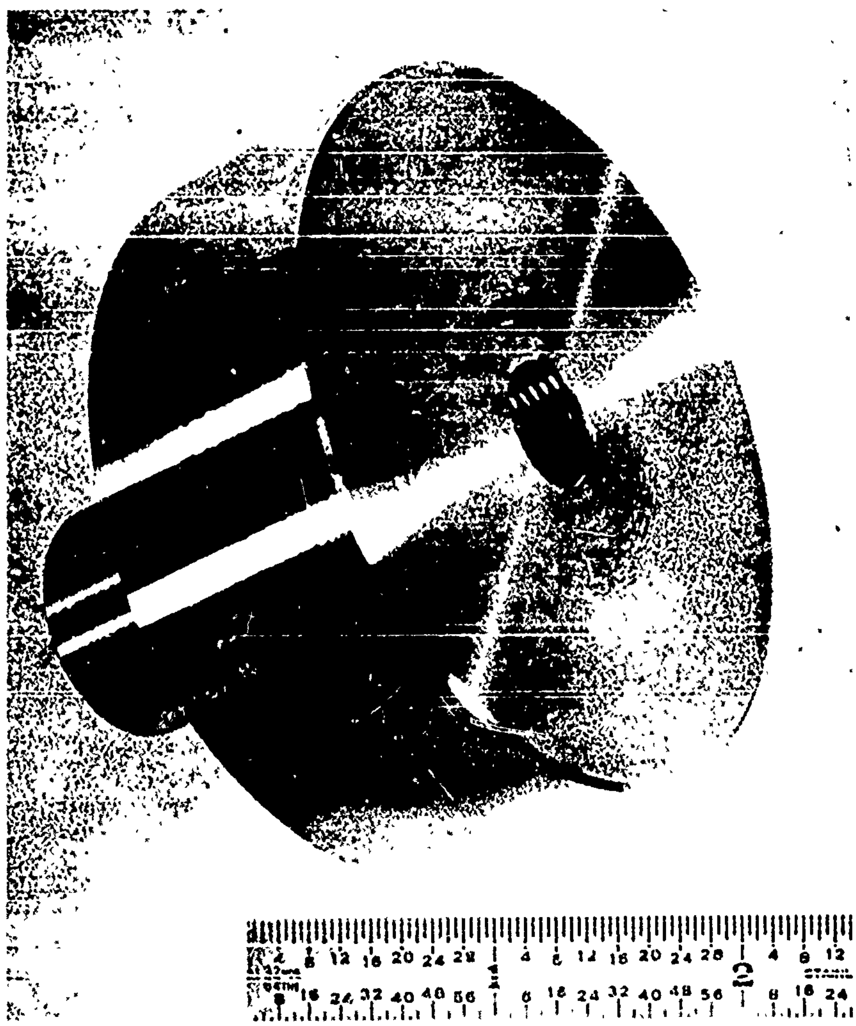


FIGURE 3 End Cap of Pressure Capsule with View of Gas Entry Port

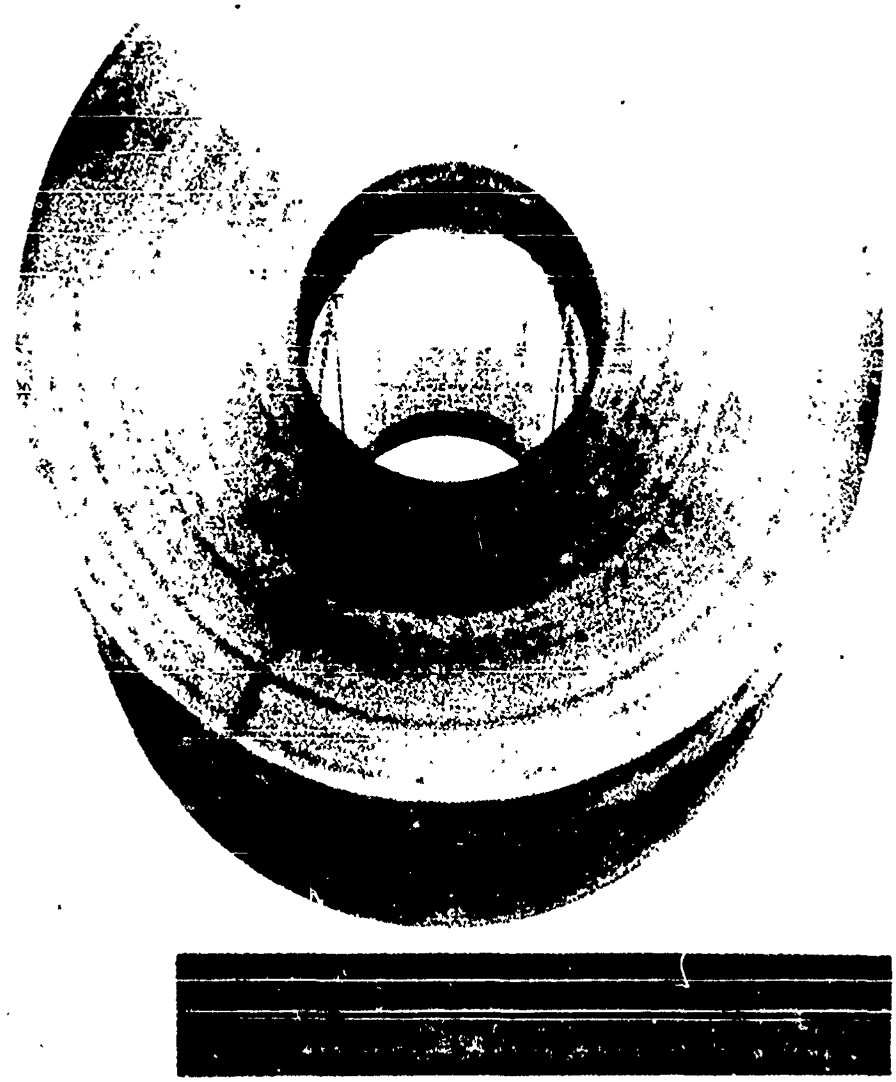


FIGURE 4 Rifled Projections on the Bore of the Tubular Section

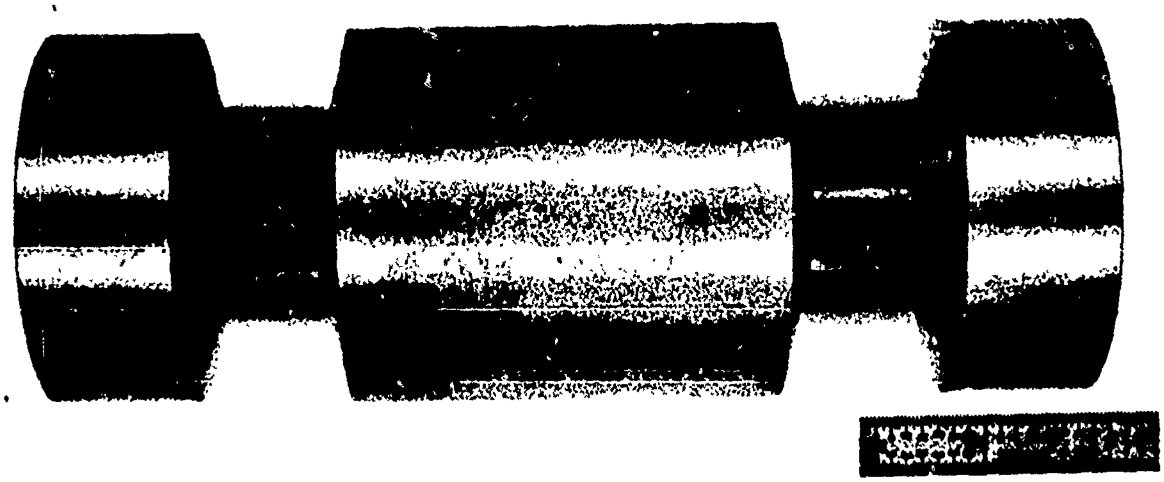


FIGURE 5 Machined SAE 4130 Pressure Capsule Prepared for Welding

2.1.3 Welding Pressure Capsules

A pressure vessel was initially produced without any liner to validate welding procedure and design performance. Welding of the end caps to the main body was carried out by use of manual metallic arc process. Weld preparation detail given in Figure 6 was selected from ASME-approved pressure vessel preparations for end closures. A weld preheat of 600°F was applied. Weld root runs were executed with Hobart Rocket LH 818 CM 1/8-inch diameter electrodes. Other runs were produced with Arcos Chromend 1MA E8018-B21, 5/32-inch diameter, 1-1/4 per cent Cr-1/2 per cent Mo electrodes. These electrodes are designed to produce matching mechanical properties with vessel material.

All welding was performed with electrodes at DC positive with a Miller direct-current power source. No mechanical tests were made on the main vessel weldments. A completed pressure vessel is shown in Figure 7. A post-weld heat treatment was carried out on the vessel at 1150°F for 1 hour at temperature. After pressure testing, a section was removed from the weld for macroscopic examination and hardness determinations. Macroscopic examination revealed a sound weld-deposit as shown in Figure 8. Some small slag inclusions and pores were noted in the weld, and care was exercised to keep these defects at a minimum. Hardness determinations in the weld and heat-affected zone yielded a maximum heat-affected zone hardness of 260-400 HV_{30}, which was considered satisfactory, and a weld hardness of 225 HV_{30}. The pressure cell was, therefore, proved for pressure application up to 10,000 psi

2.2 Gas Pressurization Facility

An air-driven gas booster compressor was used to provide the necessary vessel pressurization. The compressor was capable of a 20,000 psi maximum output at 1000 psi gas input. A triple-head version was used to apply a relatively low drive inlet pressure on the air line of 80 psig The unit is a HASKEL Model AG-233-c, capable of delivering 1.7 scfm of fully pressured gas at a gas supply pressure of 1000 psi. Argon was used as the pressure medium supplied from a normal tank cylinder at 600 psi. Satisfactory operation of the pressure facility to 10,000 psi was possible with this assembly.

A high-pressure gas circuit was designed to include a pressure gage monitor with a result regulator and an integral safety valve This arrangement provided good control over the maximum gas outlet pressure. The outlet gas pressure

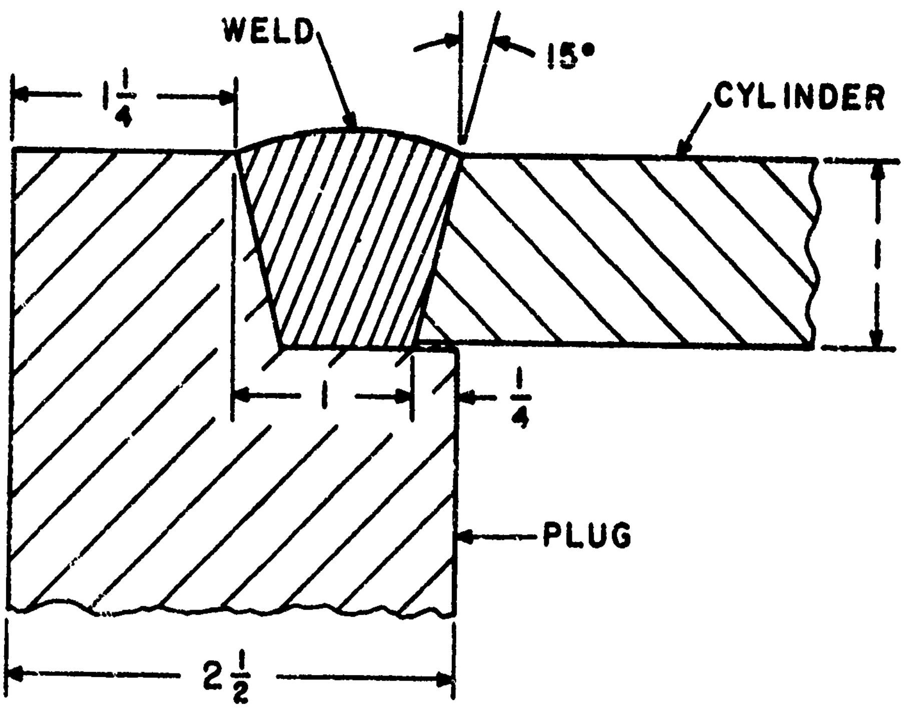


FIGURE 6 End Cap Weld Detail

FIGURE 7 Alloy Steel SAE 4130 Pressure Vessel Ready for Test

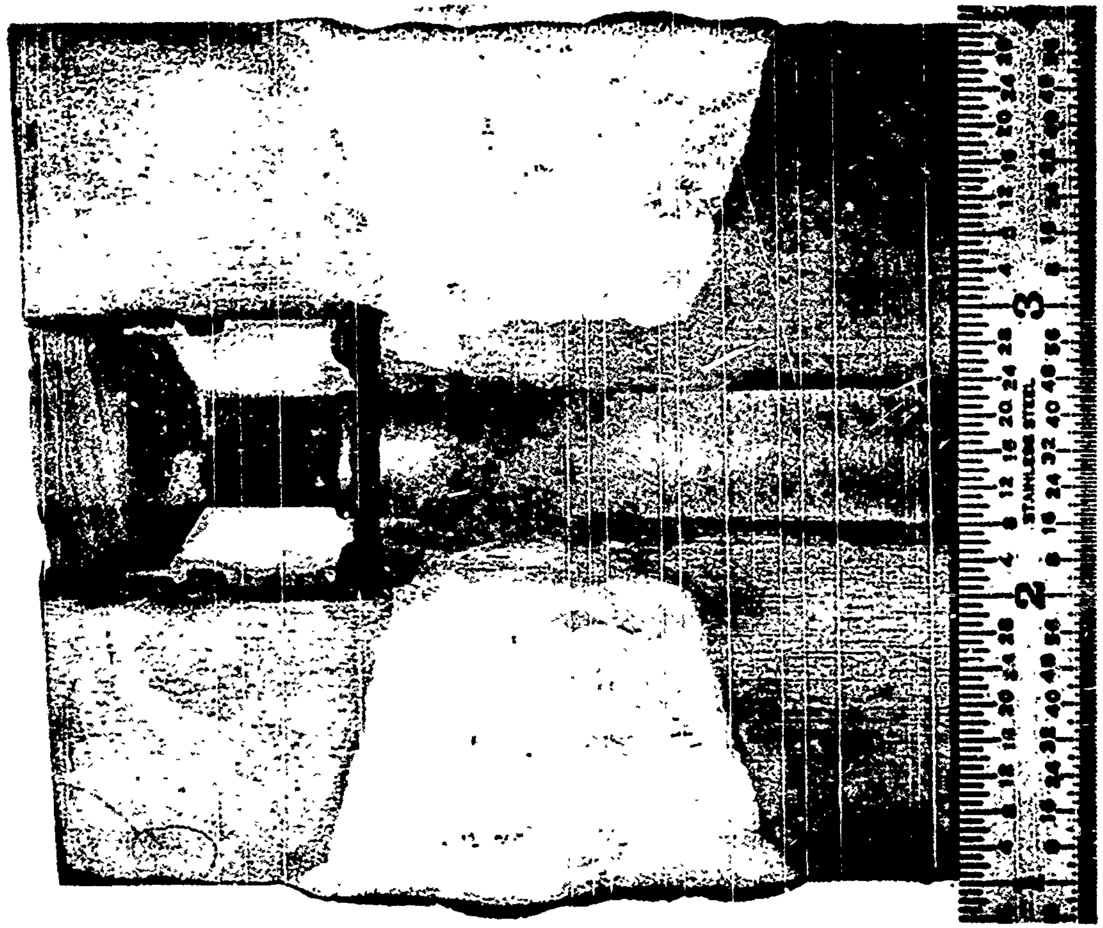


FIGURE 8 Macrosection of Main Pressure Vessel Weld

that has been preselected can be sensed by the result regulator. The air supply to the pump can be shut off to ensure the safest operation procedure. Variations in the inlet or air pressure drive system, then, do not affect the test pressure applied. Pressure settings are infinitely adjustable to the capability of the system.

The gas pressure booster system is capable of reaching pressures of 10,000 psi in approximately one minute and of performing satisfactorily throughout the program. The gas booster system, furnace, and gas supply are shown in Figure 9.

2.3 Liners

A limitation of the experimental approach was the maximum test temperature of 1000°F. At this temperature, refractory Ta-10W alloy still has a very high yield strength, which, over a projection, would allow insignificant deformation. Since metal deformation over the projection is thought to be controlled by the yield strength at the test temperature, much lower-strength materials were selected to approximate elevated temperature deformation of the tantalum alloy. In this manner, a range of material yield strengths would be possible to test and the feasibility of the concept being studied could be determined. The capacity of the projection to withstand imposed loads during processing is also important. The gun barrel material has approximately 40,000 psi yield strength and 70,000 psi tensile strength. Liner materials with yield strengths of much less than, approximately equivalent to, and higher than the strength of the projections on the gun barrel material were selected.

2.3.1 Liner Materials

Originally, the liner material was to be purchased in tubular form in diameters and thicknesses required for the program. These tubes were commercially unavailable, so purchase of strip and manufacture of tube or insert from the strip forms was necessary.

Annealed copper was purchased with a yield strength of 10,000 psi and tensile strength of 32,000 psi at room temperature in the three thicknesses selected: 0.005-inch, 0.010-inch, and 0.020-inch. Monel was selected as the intermediate strength material. This material has a yield strength of 25,000 psi to 45,000 psi, dependent upon its condition, and a tensile strength in the range of 75,000 psi to 85,000 psi. Only 0.020-inch thick material was available.

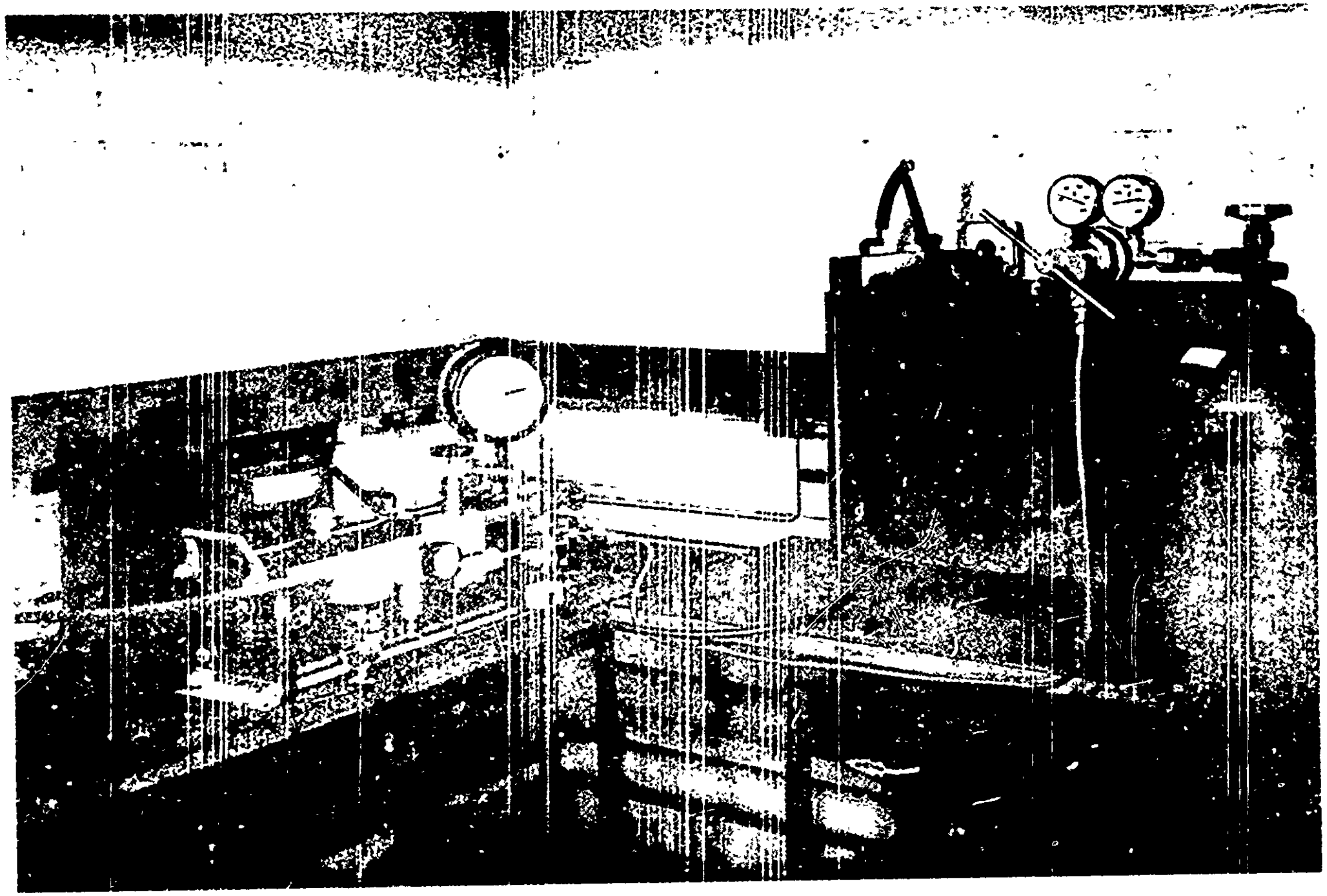


FIGURE 9 General View of Gas Pressure Pump and Furnace

The 0.010-inch and 0.005-inch thicknesses were produced by cold-rolling and annealing the as-received alloy. Finally, Ta-10W refractory material was obtained, the only material readily available being 0.005-inch thickness. Typical yield strengths of the tantalum alloy are 150,000 psi at room temperature and 90,000 psi at 1600°F. This alloy is the choice material for the liners to be used in actual gun barrels.

2.3.2 Liner Fabrication

Work commenced on the copper liners, but efforts were postponed to a later part of the program because of difficulties in fabrication of thin-wall copper tubes. Subsequently, satisfactory copper-lined specimens were produced and are discussed in later sections. Most of the effort presented here was focused on fabrication of Monel tubes in the three thicknesses.

A small melt-down lip was needed to weld the longitudinal tube joint. A weld jig was devised to hold the thin material in the required position and to provide the necessary gas protection on the reverse side of the joint. The final jig design is shown in Figure 10. The jig comprises a machined bar, slightly less in diameter than that of the required tube, with a copper tube insert, flattened to accommodate the material to be welded and slotted for allowance of argon backing gas to purge the joint area. The hold-down clamps were designed to give slightly eccentric movement upon clamping so that the material can be gripped firmly adjacent to the weld. The same jig was used for all thicknesses to be joined.

Welds were prepared with a Linde needle-arc welder with an argon-helium mixture. Excellent welds were produced in Monel in all thicknesses. Because the cylinders were rolled and welded, a 0.030-inch total clearance had to be given between the liner and the inside of the vessel. Thus, the material had to expand 0.030-inch to reach the vessel wall during test. The Ta-10W refractory alloy welds were to be made in a backfilled inert gas chamber.

2.3.3 Liner Attachment

Fabrication or attachment of the liner to the inner wall was a difficult task. The method proposed initially of simply welding the liner material to the vessel wall was impractical. Heat inputs required to melt the vessel material were too high for the liner, and satisfactory welds could not be made

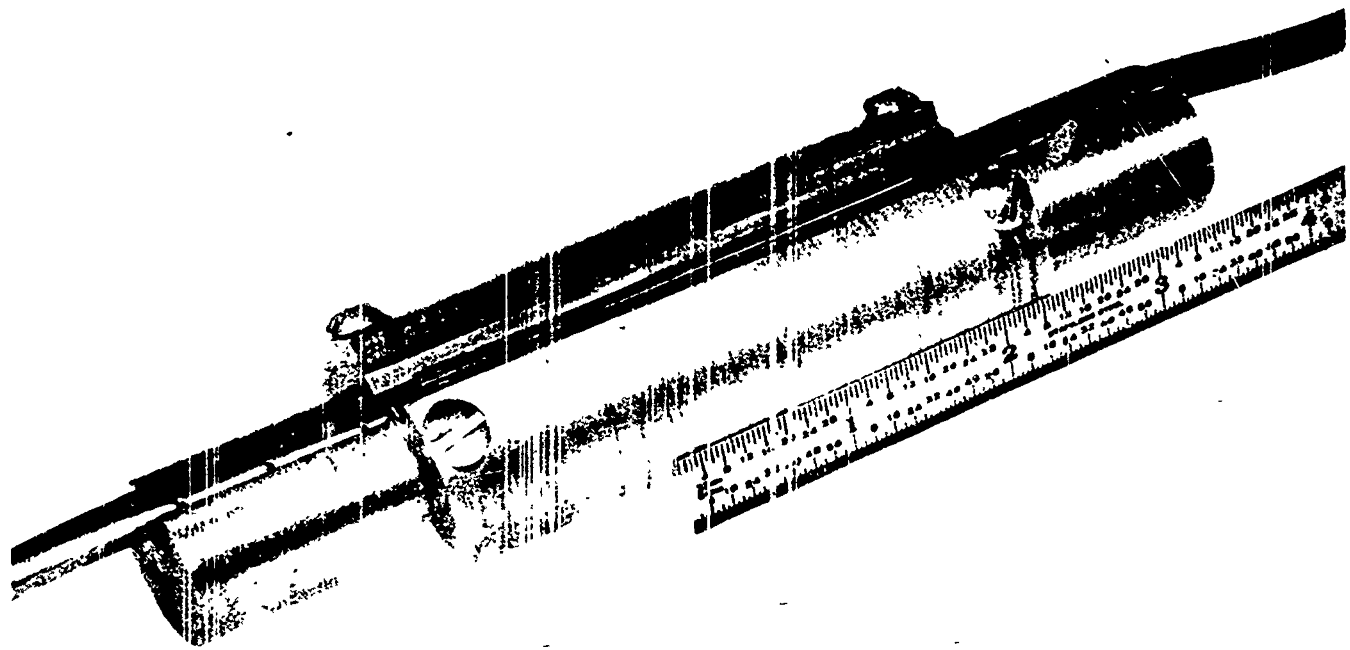


FIGURE 10 Welding Jig for Liner Fabrication

A relatively large mild steel insert was used for welds to the vessel wall. The insert was suitably machined to form a projection that could be melted at a rate comparable to the liner. Several attempts were made at insert design before a satisfactory item was produced. Details of the inserts are given in Figure 11. Three sizes of inserts are necessary to produce good welds. The projection "h" was melted down with the edge of the tubular liner to form the inner sleeve. A fabricated inner sleeve comprising the liner with one insert at each end is presented as Figure 12. The vacuum liner brazed into position for evacuation of the envelope between the liner and barrel before test can be seen. The vacuum system was modified later. Excellent weld joints were produced with the method by use of the plasma needle-arc welder and nickel alloy filler wire. Metallographic examination confirmed the sound weld procedure.

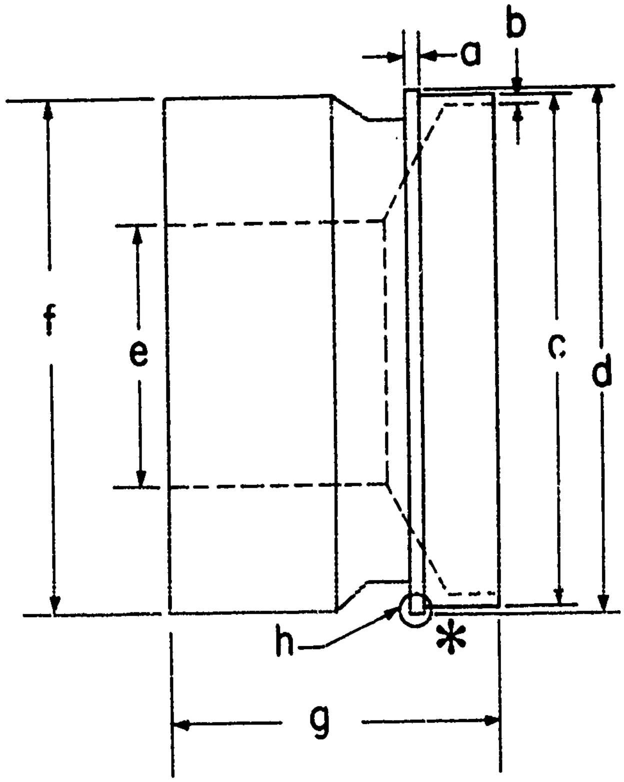
Welding copper liners by this method was unsuccessful. The copper liner had to be brazed to the insert by a torch-brazing technique and silver-bearing braze alloy. This approach worked well, although some concern was necessary since weldments had to be produced adjacent to the braze and remelting of the braze alloy could occur.

2.4 Welding Fabricated Sleeve to Pressure Vessel

The large mild steel insert facilitated the joining of sleeve to the main pressure vessel The vessels were heated to 600°F to prevent underbead cracking, and the insert was welded with a pure nickel filler rod and the gas tungsten arc process. Some minor crater cracking was encountered because of joint restraint, but this was eliminated by use of a current downslope technique at the end of the weld. Metallographic examination of the fillet weld revealed a sound weld deposit with no evidence of cracking in the main pressure container.

2.5 Vacuum Between Liner and Vessel

Vacuum test procedures were instituted at each stage of vessel fabrication. Stage one comprised a vacuum test on butt-welded liner cylinders. A second test was made after the liners had been fabricated to the insert. A third vacuum test was imposed after the brazing of vacuum tubes in position. Finally, a test was performed after the fabricated liners were welded to the main pressure vessel. The samples must be capable of pulling a vacuum of less than 1 micron at each stage, with a negligible leak rate.



Monel Liner Thickness, in.	Dimension, in.							
	a	b	c	d	e	f	g	h (area, sq. in)*
.020	.044	.025	.930	.985	.500	.985	.650	.00121
.010	.030	.025	.950	.985	.500	.985	.650	.00053
.005	.025	.020	.970	1.00	.500	.985	.650	.00038

FIGURE 11 Design of Mild Steel Insert

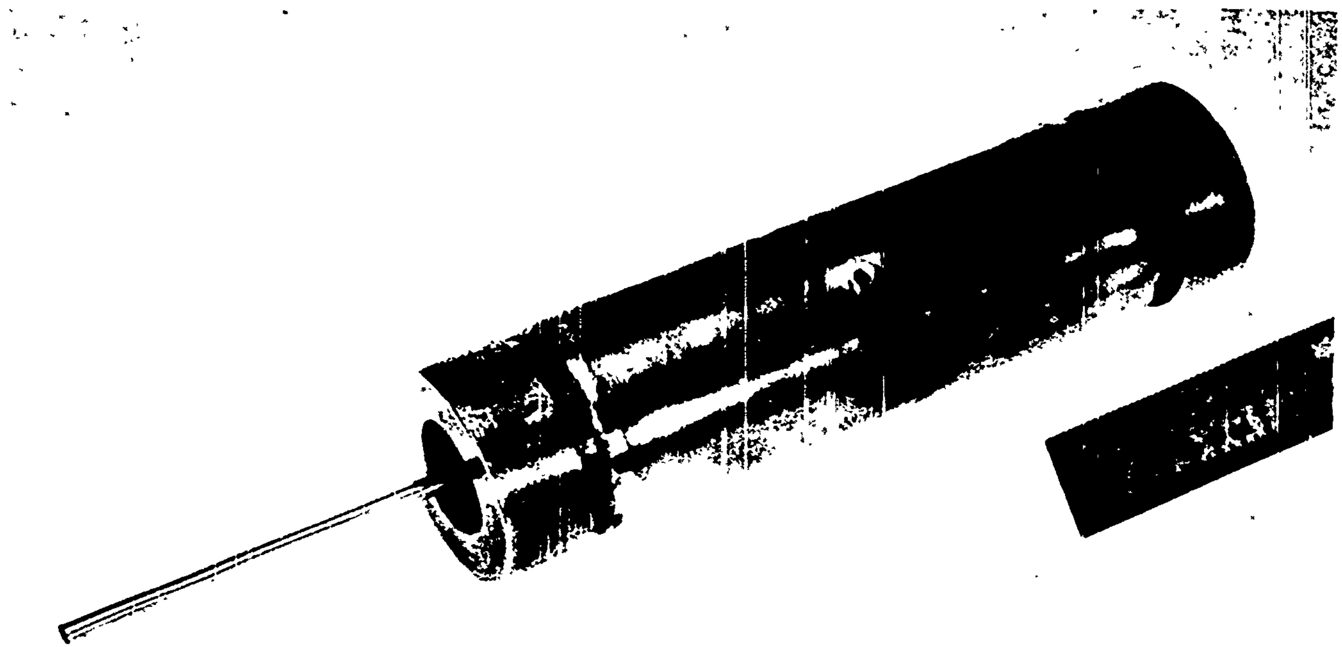


FIGURE 12 Monel Liner with Vacuum Tube Attached Ready for Insertion into Pressure Vessel

Even low-leak rates were not allowable since the pressure cell had to be sealed off at the next stage, and the vacuum condition maintained between liner and pressure vessel wall while the remaining part of the fabrication procedure was completed.

The vacuum sealing-approach was inadequate since the use of this approach did not provide allowance for outgassing of parts at elevated temperatures nor was the use proved to be 100 per cent effective. An example of a test in which the vacuum between the liner and the vessel failed is shown in Figure 13. In this case, pressurization and expansion of the liner caused a small leak in one of the weldments. Gradually, the pressure behind the liner must have equalized. On release of the internal pressure, the liner then collapsed since the trapped gas could not escape quickly enough.

Subsequently, similar vacuum test procedures were carried out in the early stages. Instead of a vacuum line attached to the liner, a small hole was drilled in the pressure vessel wall located at the insert, and a permanent vacuum line was attached to the outside of the pressure vessel. A vacuum could then be continuously pumped throughout the experimental cycle, and very small leaks and outgassing could be accommodated without any problems.

3. TEST PROCEDURE

Pressure vessels with liners of appropriate thickness were welded as previously described. A final stress relief was given to each vessel before pressurization. The test vessel was placed in the furnace and vacuum-pumped overnight. The furnace temperature was raised to the test temperature during continuous pumping. After temperature equalization, the pressure was raised approximately 2000 psi per minute with argon until the test pressure was reached. Specimens were allowed to remain at full pressure and temperature for 30 minutes. Bleeding through a valve was used to release the pressure while a vacuum was continuously maintained between the liner and vessel.

After the test run had been completed, one end of the pressure vessel was drilled out. A cold-curing liquid epoxy compound was poured into the vessel and allowed to solidify. Sections were then removed from the vessel for examination. A sample is shown in Figure 14. Two slices approximately 3/4-inch thick have been removed so that two positions along the container are visible.

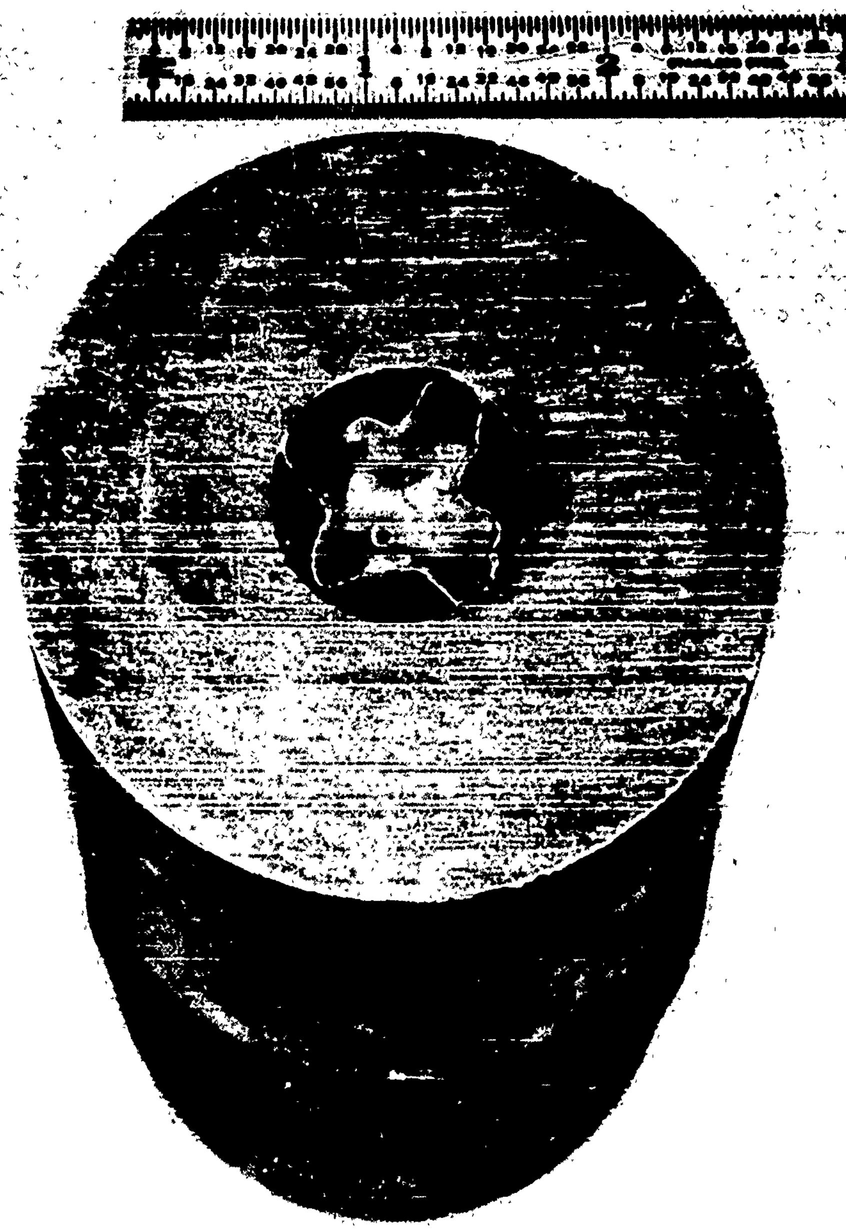


FIGURE 13 Liner Collapse due to Leak Between Liner and Vessel

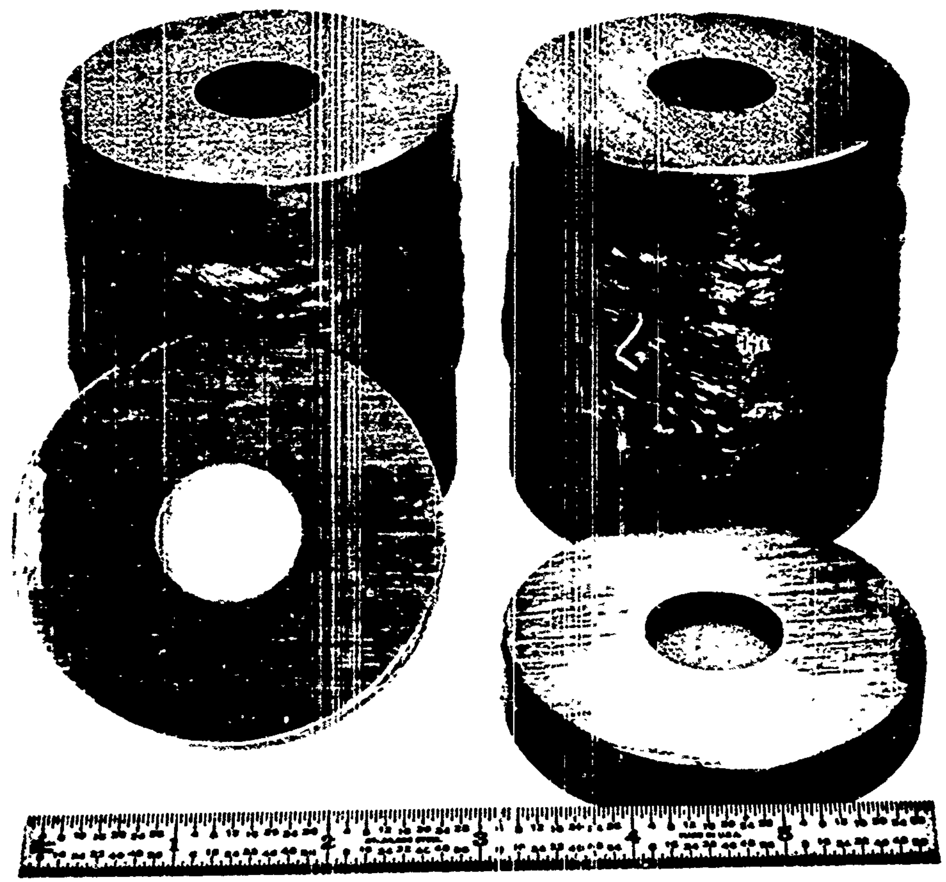


FIGURE 14 Short-Length Tubular Sections with Sections Removed for Examination of Liners

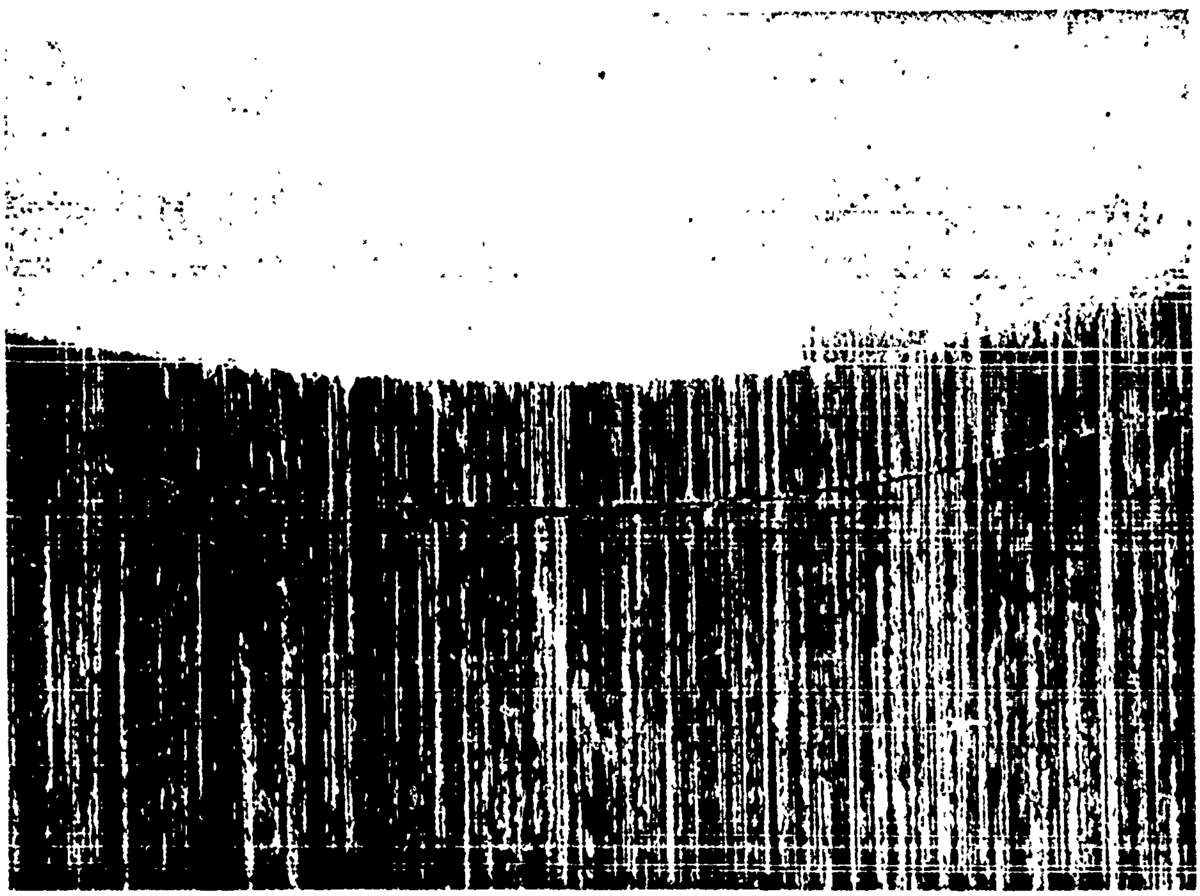
4. TEST RESULTS

Satisfactory liner fabrications were most readily made with Monel. Liners were produced initially from 0.020-inch-thick material and subsequently from 0 010 and 0.005-inch-thick materials by the techniques described. Pressure application to Monel did not produce any substantial difference in results between room temperature and 1000°F. Thus, work was focused mainly on the maximum parameters of 1000°F and 10,000 psi pressure for approximately 30 minutes under test conditions

Pressure application with 0 020-inch thick material did not provide significant movement of the liner in the region adjacent to the projections. No evidence of replication of the projection features at the inner surface of the liner could be discerned. The 0 020-inch liners contact the tube wall approximately 0.08 to 0 10-inch from the edge of the projection. An illustration of room-temperature pressure application is given in Figure 15. Increasing the temperature to 1000°F at the same pressure did not improve the profile conformity (Figure 16)

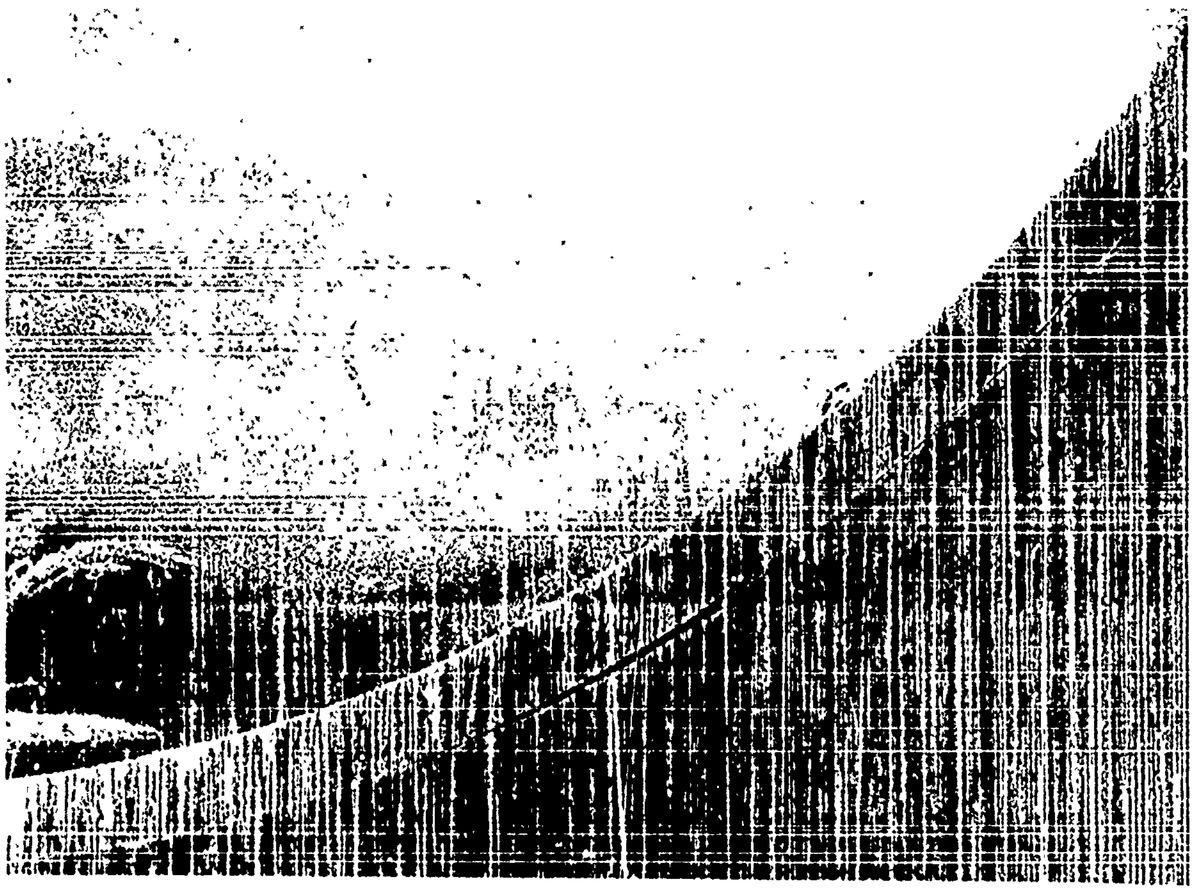
Gas pressure application to annealed 0.010-inch thick Monel produced the samples shown in Figures 17 to 19. All these tests were performed at 10,000 psi pressure. Distances between the edge of the projections and contact with the gun barrel wall were 0 025 to 0.030-inch. As illustrated in the figures, variations in the angle of projection do not occur in the final results with the parameters used Some work-hardening does occur during the liner fabrication procedure To ensure maximum benefit of all available ductility, all the 0 010-inch and 0.005-inch liners were annealed at 1600°F for 10 minutes at temperature before insertion in the main pressure vessel A pure argon atmosphere gettered with titanium sponge was used to retain a bright, clean surface finish

Examples of specimens produced in 0.005-inch-thick material are shown in Figures 20 to 22 Generally, the thinner gage material produces much better replication of the liner shape This result is particularly evident in Figure 20 However, closer examination of the samples discloses that gaps still exist between the liner and the edge of the projection These gaps cannot be permitted for gun barrel application Specimens shown in Figures 20 to 22 were prepared by a continuously pumped vacuum-system having a hole drilled through the main vessel wall Consequently, because of vessel design, the applied pressure had to be reduced and was fixed at 8500 psi No problems were encountered.



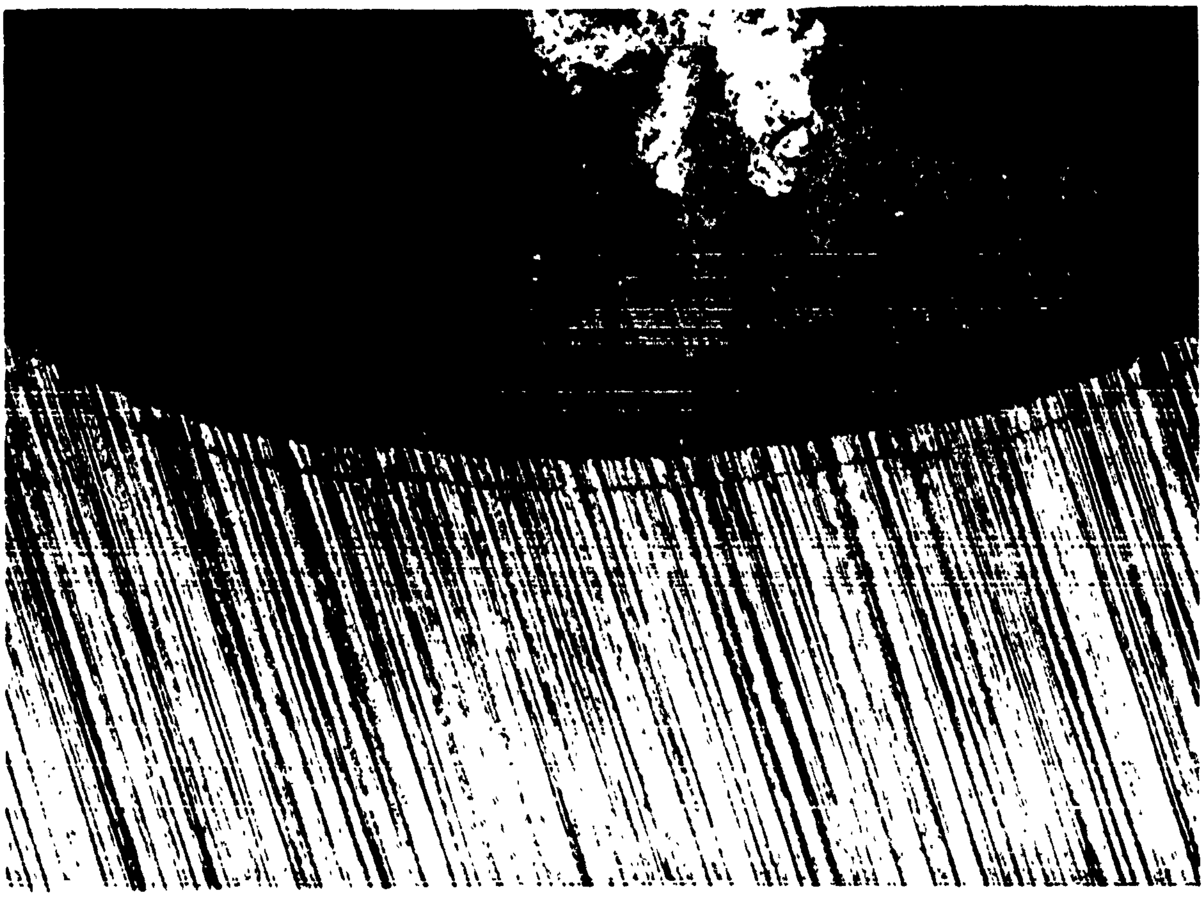
X30

FIGURE 15 Liner of 0.020-Inch-Thick Monel over Projection after 10,000 psi at Room Temperature



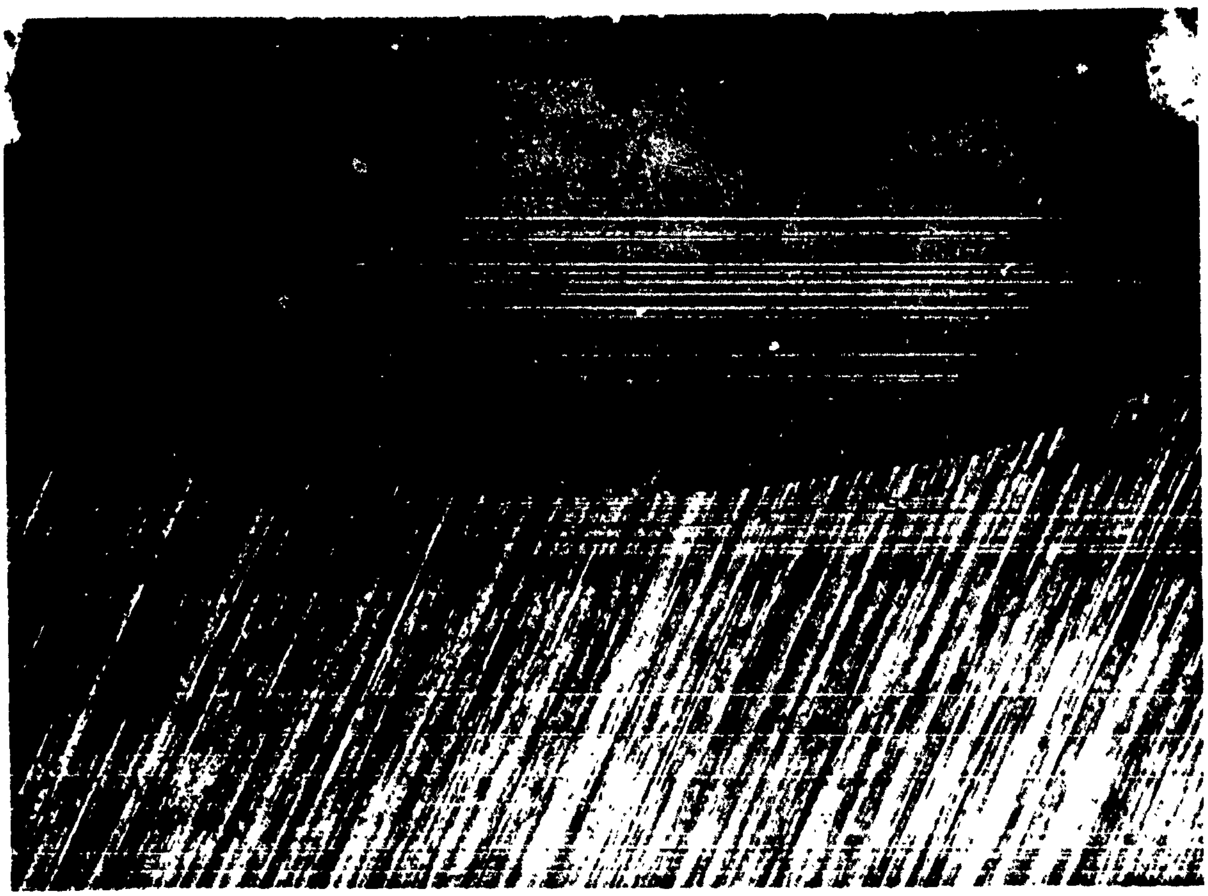
X25

FIGURE 16 Liner of 0.020-Inch-Thick Monel over Projection after 10,000 psi at 1000°F



X15.6

FIGURE 17 Liner of 0.010-Inch-Thick Monel with View of Good Contact except for Projection Edge, 75° Angle

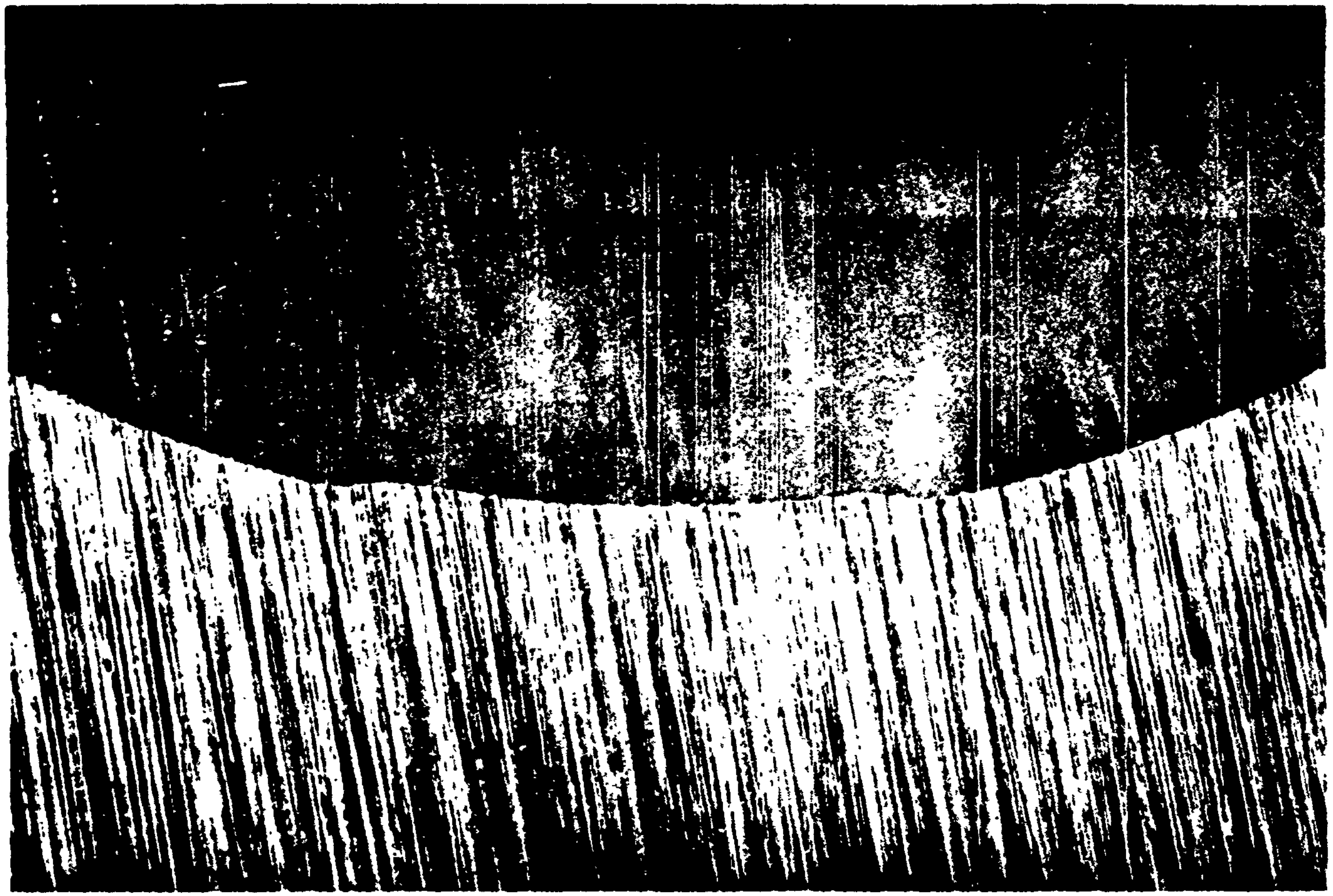


X16.3

FIGURE 18 Liner of 0.010-Inch-Thick Monel with View of Good Contact except for Projection Edge, 90° Angle

X16.3

FIGURE 19 Liner of 0.010-Inch-Thick Monel with View of Good Contact except for Region of Projection Edge, 45° Angle

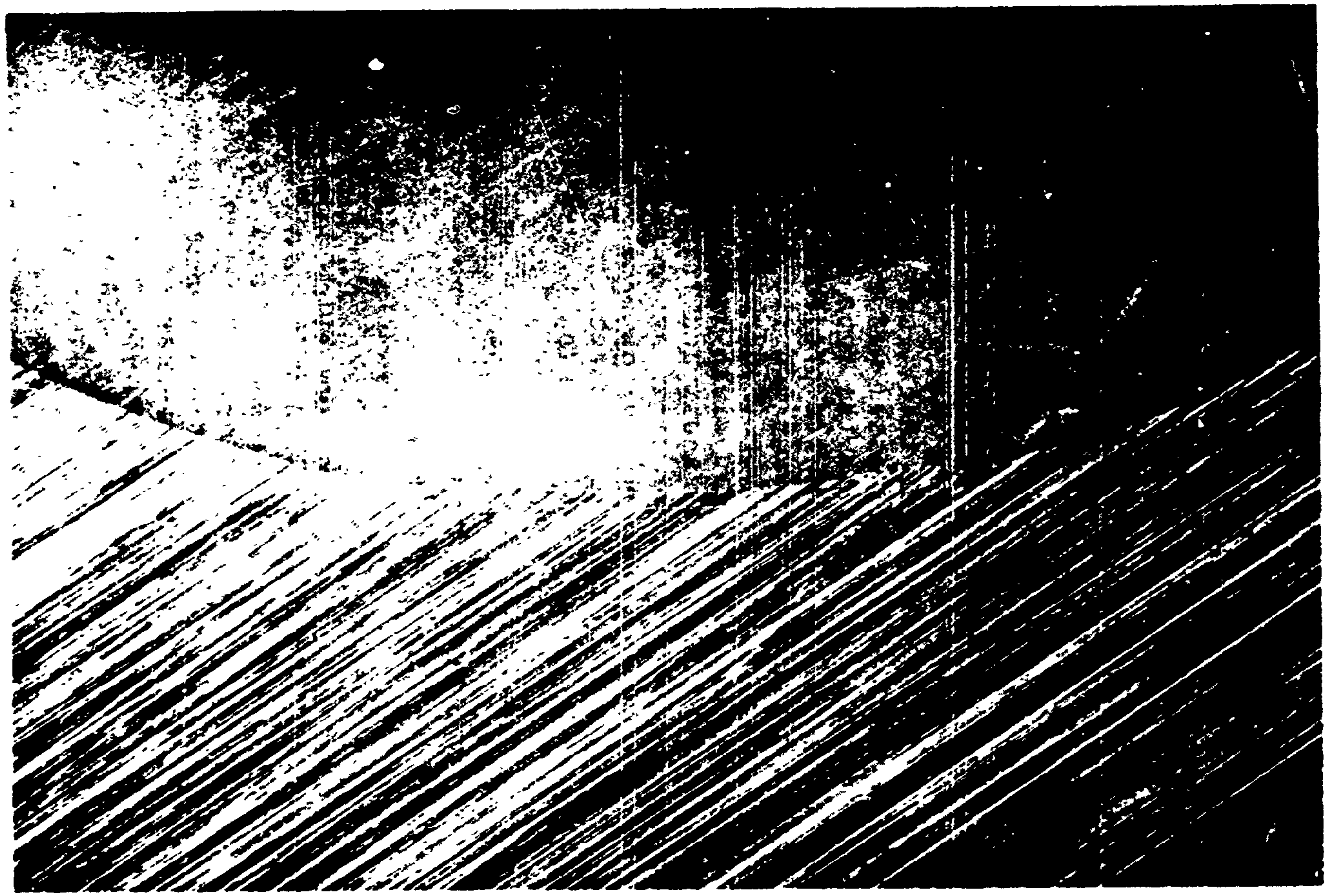


X15

FIGURE 20 0.005-Inch-Thick Monel Liner with View of Improved Conformity to Thinner Gage, 90° Angle

X15

FIGURE 21 0.005-Inch-Thick Monel Liner with 75° Angle Projection. Smaller Gap Adjacent to Projection



X15

FIGURE 22 Monel Liner, 0.005-Inch-Thick with 45° Angle, Gap at Edge of Projection

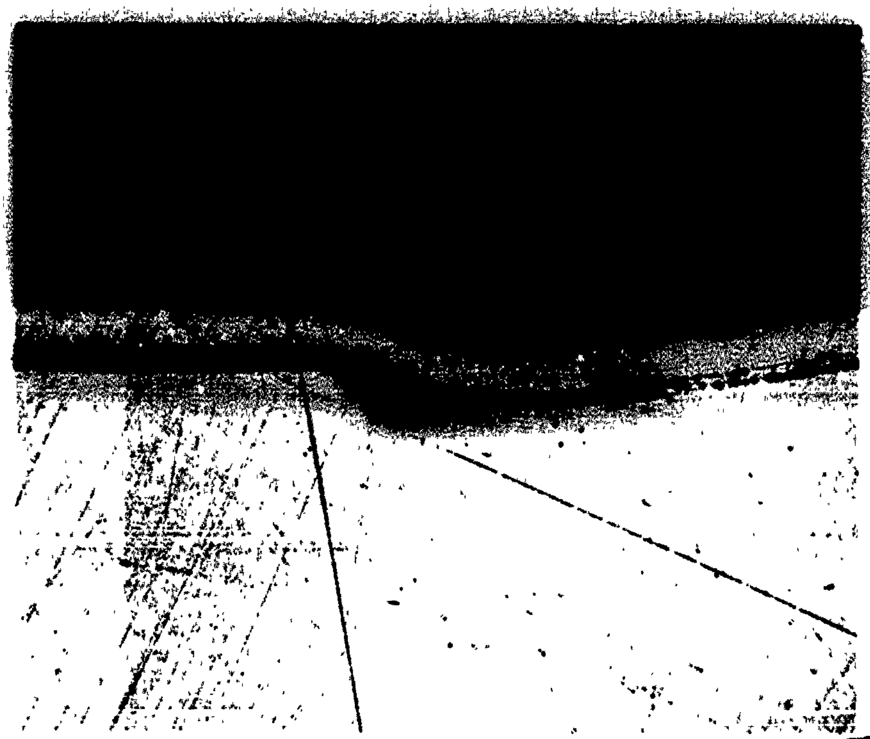
Microscopical preparation of these samples proved difficult because of the springback occurring in the liner when the tube section was cut. One specimen of the 0.005-inch-thick Monel is shown in Figure 23. The specimen as prepared is shown in Figure 23a; the specimen as it would have appeared under test pressure is shown in Figure 23b. Samples 0.005-inch-thick had gaps varying in the range of 0.015 to 0.020-inch. The sample in Figure 23 has a 0.020-inch gap.

The observations noted above disclosed a possible relationship between the distance from the projection edge to the point of contact with the steel wall and the yield strength of the material, or its thickness.

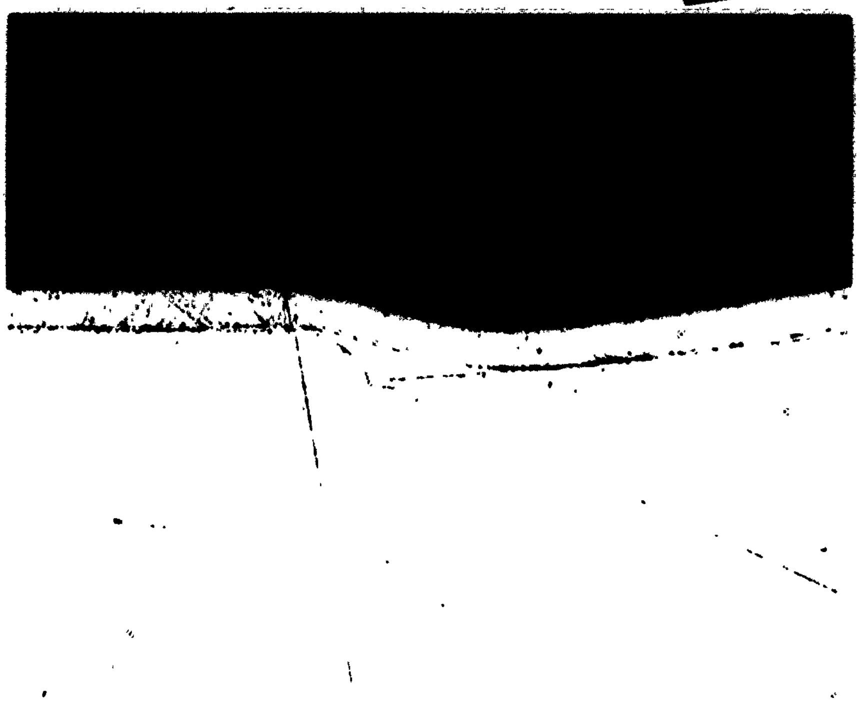
A copper liner, 0.010-inch thick, was fabricated and pressurized at 5000 psi. The vessel was sectioned for examination, and good contact with the tube wall was demonstrated. Again, in the area of the projection, a gap occurred between the projection edge and the tube wall. With the 0.010-inch-thick copper liner (Figure 24), a gap of 0.021 inch was measured. If gap width is assumed to be directly related to material thickness and inversely related to applied pressure, the result cited above can be predicted. A review of test data appears to corroborate this hypothesis. A simple rational explanation of the results achieved has been proposed and could probably be used to predict future results. This finding is discussed in a later section.

5. AN EXAMINATION OF A G.E PRELIMINARY TEST

One sample has been received that was made at General Electric, Cincinnati Although the sample is from a preliminary test only, some important features of the probable effects of the attachment of tantalum alloy liners to SAE 4130 steel are clearly demonstrated in Figure 25. The outer sleeve shown is SAE 4130 steel with a 0.10 by 1/8-inch wide groove. The liner is Ta-2.5W alloy, 0.015-inch thick. The liner was applied as a slip fit to the sleeve and edge-brazed with copper by the electron beam process to form an evacuated envelope. The sealed liner was then isopressed for 30 minutes at 1600°F followed by 5 hours at 1850°F No evidence of actual bonding exists between the liner and the steel even after exposure at 1850°F Conformance of the tantalum alloy liner to the projection (which in this case is a groove) has not occurred Some evidence of a shear edge on the tantalum liner and slight deformation of the steel is present. Although not shown in the photomicrograph, the tantalum liner actually fractured at its inner surface coincident with the edge of the groove Another point of interest is evident at



(a)

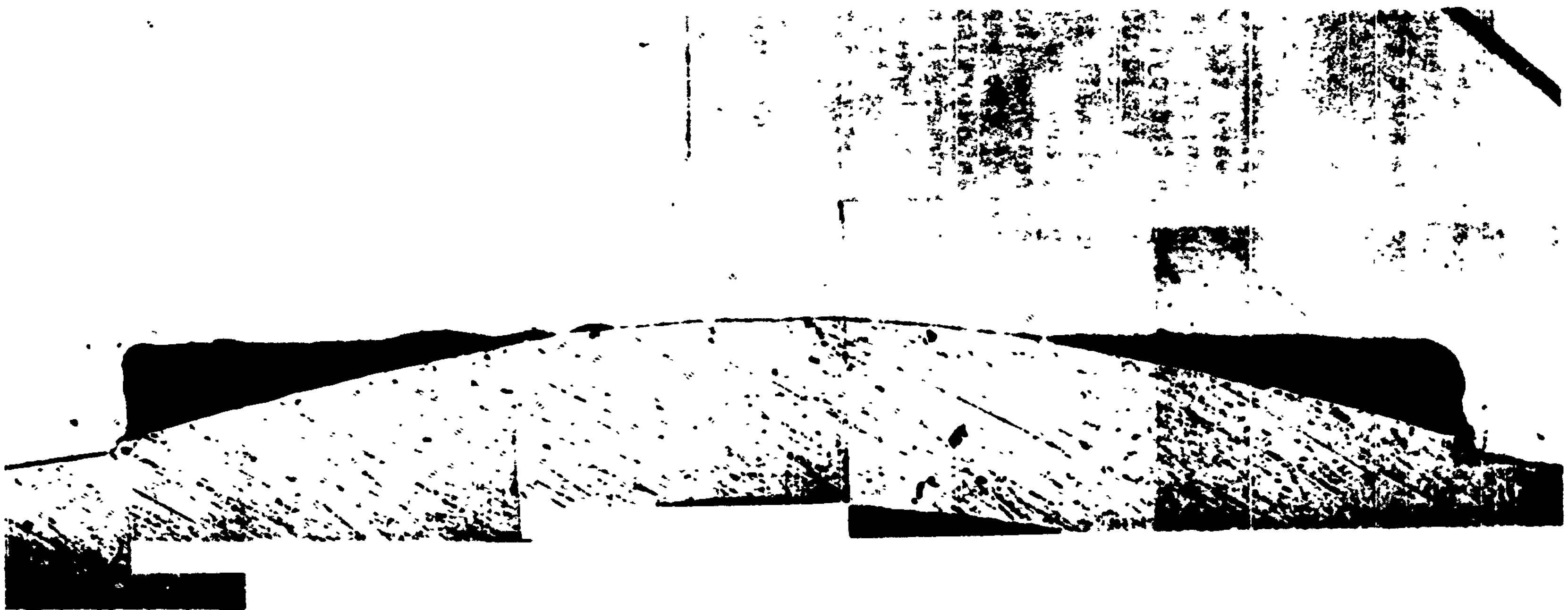


(b)

X50

FIGURE 23 Monel 0.005-Inch-Thick Cross Section with View of
(a) Springback during Preparation,
(b) Projection and Liner as Pressurized.

FIGURE 24 Copper Liner 0.010-Inch-Thick after Pressurization at 5000 psi X56



100x
As "polished"

X100
(Reduced to
2/3 size)

FIGURE 25 Tantalum Alloy Liner Gas-Pressure Bonded to SAE 4130 Steel the center of the groove. The tantalum liner has deformed the steel at the center of the groove because of the superior strength of the liner at the gas pressure bonding temperature. This behavior reveals that the liner is more likely to deform the projection than be deformed.

6. DISCUSSION

During the initial stages of pressure application, the internal sleeve or pressure vessel expands toward the wall of the outer vessel in a relatively uniform manner. The internal pressure creates a tensile stress in the cylinder $\sigma_s = pd/2h$. In one case, the applied pressure is 10,000 psi with a nominal 1-inch diameter and a 0.005-inch wall thickness. Stress applied is therefore 1000 kpsi, and the liner is forced against the wall. Once the liner reaches the wall, however, a different case exists in the area of the projection. Perhaps the following observation is an oversimplification: the assumption, however, is that the material now behaves as if it were a rigidly supported simple beam. At what point would the beam be capable of supporting the applied 10,000 psi load without further deformation into the corner of the projection?

Re-examination of the test data shows that the Monel liner of 0.020-inch thickness and yield strength of approximately 40,000 psi results in a gap of 0.10 inch at the base of the projection, whereas the 0.010-inch liner in Monel annealed before test and probably with a yield strength of 25,000 psi leaves a gap of 0 025-inch or 0.040 inch when not annealed.

A simple calculation of the effective load between the projection edge and the point of contact with the tube wall reveals that the material does indeed behave as if it were a simple supportive beam. The length of material from the edge of the projection to the point of contact can then be predicted if yield strength of the material, thickness of the liner, and applied pressure are known.

The additional elastic movement during the test, again on the basis of simple beam deflection calculations, can be considered practically negligible at the test parameters.

Accordingly, projection of data can be considered for all materials, thicknesses, and temperatures of gas pressure application provided the yield strength of the material at any given temperature is known. Predicted information is presented in the next section on the basis of this hypothesis.

The material must be at or above its flow stress at the particular strain rate and temperature imposed on the specimen so that movement into the corner of the projection can be obtained. The conditions of high temperature and high pressure necessary for the examination of the liners, in this manner, cannot be achieved under the present experimental setup and would be extremely difficult to achieve practically. With high projection angles, the only conditions indicated under which a reasonable facsimile of the projection can be produced are those involving extremely thin liners and force exceeding the liner material flow stress during the test. With a 0.005-inch high projection, the liner thickness is estimated to be less than 0.001 inch to provide reasonable conformity to the projection surface. Provisions of some radii at the projection corners would help in producing a satisfactory lining arrangement, especially if the subject material has low ductility values.

To facilitate liners of several thicknesses for the present program, alloy of one size was purchased, rolled to the required thicknesses, bent into a tube shape, and longitudinal seam-welded. This method has proved troublesome because, for effective joining, specific jigging is required for each thickness, and welding procedures must be individually developed. Practical limitations in the production of liners in this way have required approximately 0.030-inch clearance between the completed liner tube and the pressure vessel wall. Some ductility is, therefore, exhausted in pressing the liner against the wall. For prototype gun barrel manufacture, only slip-fit seamless tubes are recommended to provide the maximum available ductility for forming, around the projection, and the minimum risk of rupturing the liner during the gas pressure joining process.

Defining the bonding parameters for tantalum alloy liners is still questionable. In this program, no evidence of bonding has been observed between the nickel alloy and the steel pressure vessel at temperatures up to 1000°F and at an applied pressure of 10,000 psi Obviously, no bonding of the tantalum alloy will occur at these parameters either. Generally, the rule of thumb used for the onset of diffusion bonding is that the materials involved must be subjected to a temperature of at least 0.4 T_m, which is approximately 1400°F for nickel and steel. With dissimilar metals, the particular metal couple probably indicates whether the lower or higher melting material will satisfactorily create a contact surface area sufficient for interface diffusion to occur. With the use of the Ta-10W alloy as the example, a temperature for satisfactory bonding will be at least 2500°F.

A relatively high bonding temperature and a very thin liner are necessary to achieve the desired lamination. The procedure cannot be carried out on a finished gun barrel, but it must be performed at an intermediate production stage. Possible deformation of the projections at the high bonding temperatures must be considered. From these considerations, direct bonding tends to become unsuitable.

7. PREDICTED LINER PROFILES

Test results have revealed the possibility of a relationship between liner yield strength at bonding temperature, projection profile, and applied gas pressure by which the capacity of a liner to assume the shape of a projection on the inner surface of a gun barrel is determined.

The form and validity of this relationship have been explored to examine the feasibility of producing a predictive result. On the assumption of the load-supporting beam concept, the free length of liner adjacent to a projection can be estimated by multiplication of the yield strength of the material and its thickness, and division by applied pressure to maintain the load without further deformation. The result is graphically presented in Figure 26, with liner thicknesses from 0.001 to 0.020-inch.

Actual test data were then taken and superimposed on the graph. With allowance for alternative test pressures and yield strengths of the materials used in the program, a good fit is obtained. The yield strengths are estimated; but, even with possible error, the data points are of the correct order and tend to substantiate the contentions made. Preferably, further tests should be carried out now to provide further proof, but this action is impossible on the present program. However, the results are so interesting that the relationship for all important parameters was examined to estimate the practical possibilities of liner materials and rifling projections.

A projection angle of 45° was chosen for the data presented in Figure 27. The maximum yield strength material that may be used to produce profile conformity with varying projection height at selected liner thicknesses is predicted by the lines. This presentation shows clearly that a Ta-10W liner at 1600°F and 10,000 psi applied pressure must not be thicker than 0.001-inch with a projection height of 0.007-inch and 45° angle to achieve conformity to the surface.

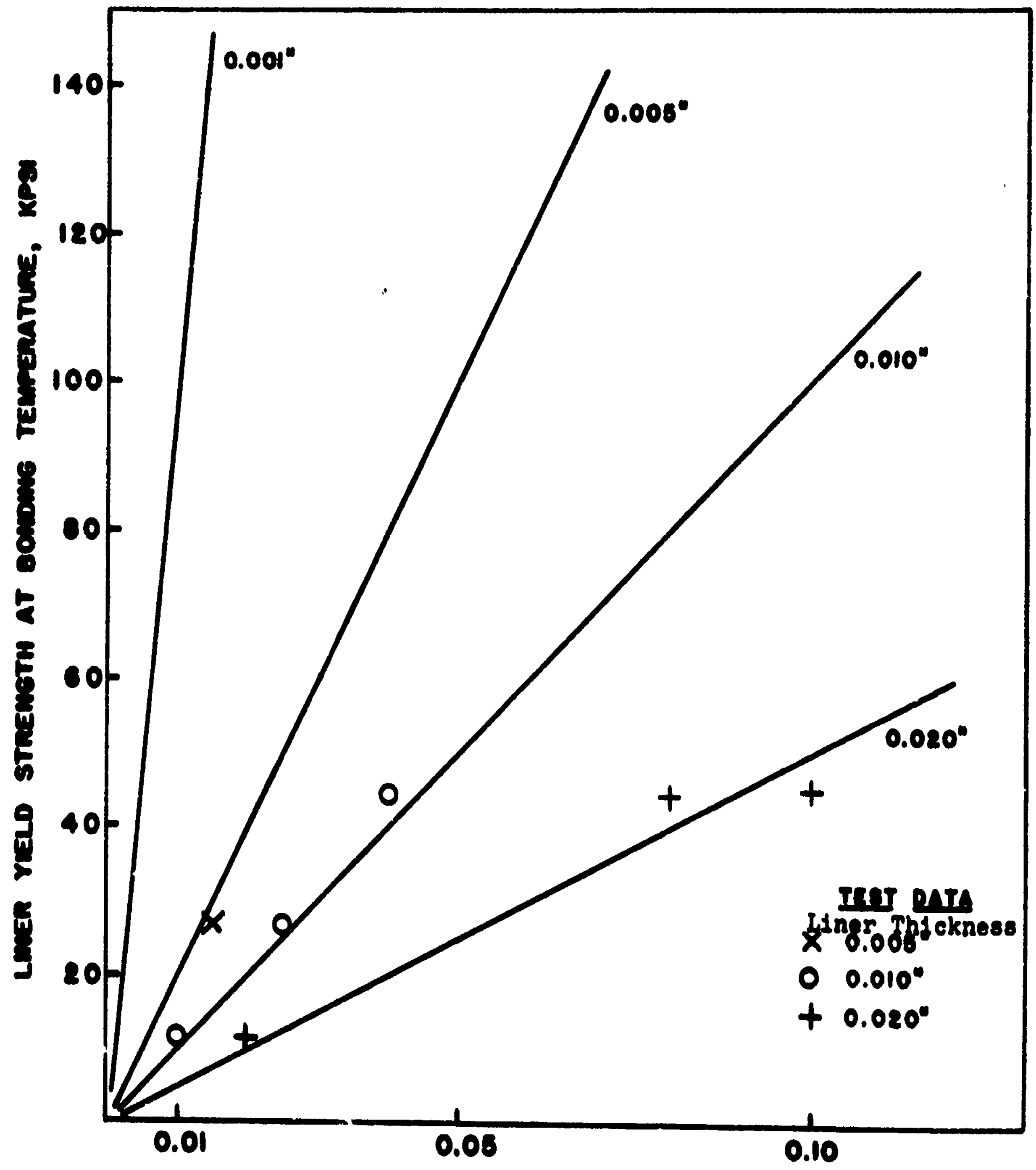


FIGURE 26 Free Liner Length at Bonding Temperature with 90° Projection Angle and 10,000 psi Pressure

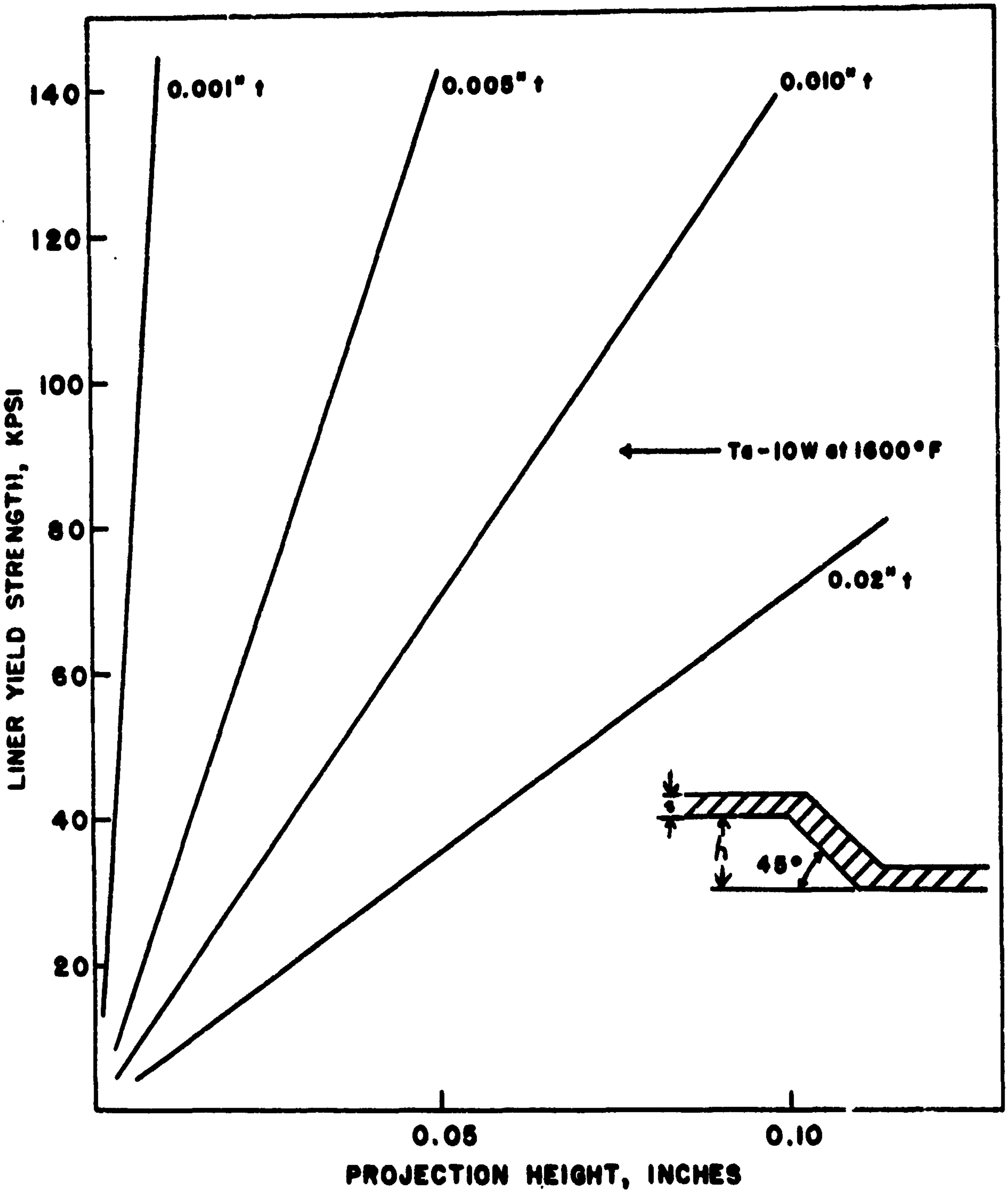


FIGURE 27 Projection Height Necessary for 45° Angle Conformity to Various Liner Thicknesses and to 10,000 psi Pressure

A different plot is made in Figure 28 to illustrate the strong influence of liner thickness on the capacity to conform to a surface, especially at small projection heights. The plot shows that, to produce required results with an 0.008-inch-thick liner of tantalum alloy, a projection height of at least 0.050 inch is needed. The influence of the projection angle is illustrated for two projection heights in Figures 29 and 30. In these figures is shown how the low-angle projections help to improve liner conformity to profile.

All predictive graphs, Figures 26 to 30, were constructed at 10,000 psi pressure. However, since pressure affects the result inversely in a linear manner, substitution of the desired pressure is easily accomplished. Besides, the following formula may be used to calculate the estimated gap with 90° projections:

$$\text{Length of gap} = \sqrt{(\sigma_y t/p)^2 - h^2}$$

where σ_y = liner yield strength at test temperature, psi

t = liner thickness, in.

p = test pressure, psi.

h = projection height, in.

Consideration of the validity of the predictions presented in Figures 26 to 30 reveals that the concept probably applies fairly accurately to projection angles of less than 60°. An increasing degree of error will occur at higher angles because of localized work-hardening and because of the reduced effective beam length in the final stages of profile formation. However, the rules appear to be generally applicable to determine whether a particular series of experiments are likely to succeed. The rules clearly demonstrate that Ta-10W liners of sufficient thickness for practical use cannot reproduce the gun barrel projection profile.

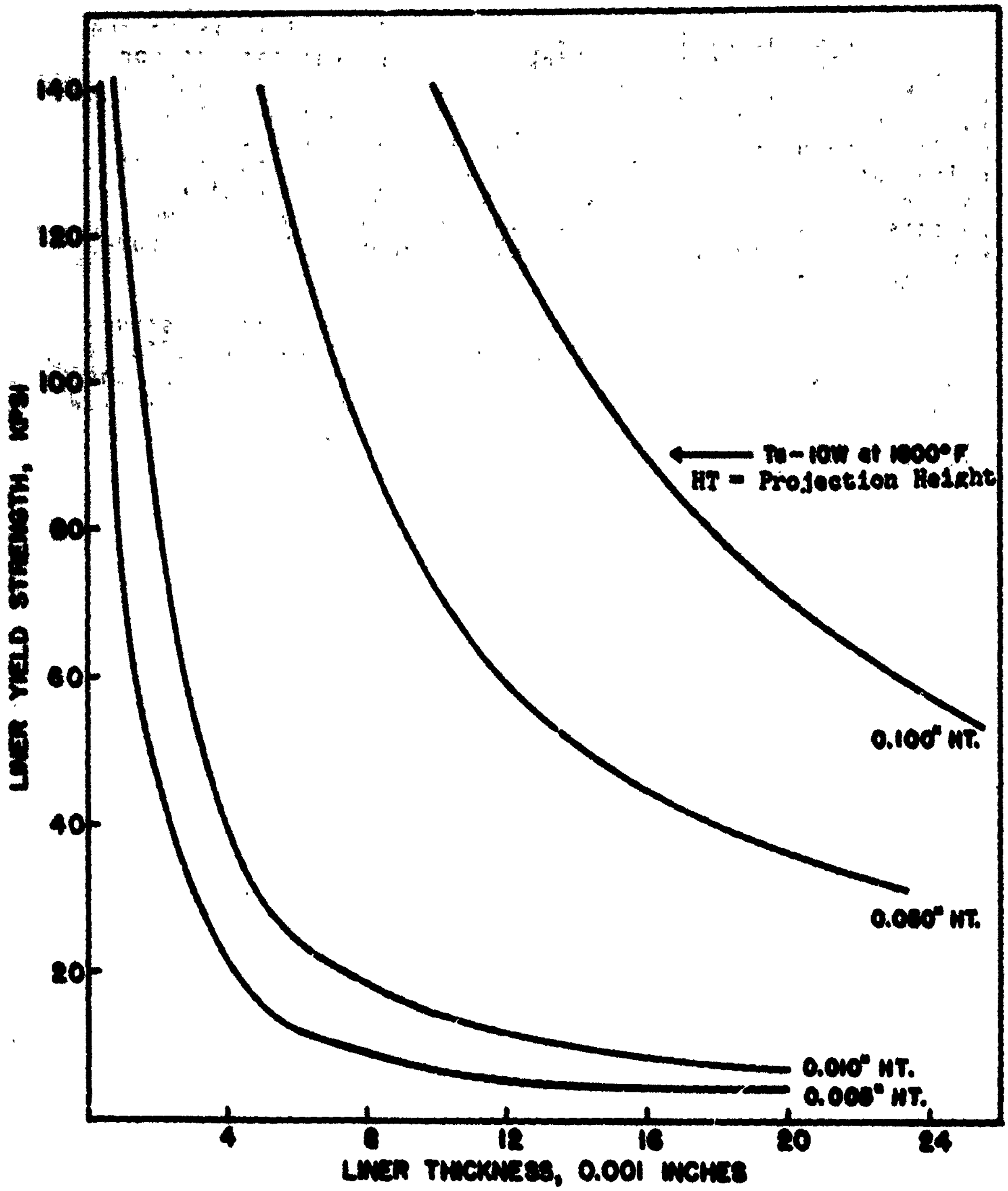


FIGURE 28 Predicted Parameter Relationships for Maximum Yield Strength Requirement for 45° Conformity

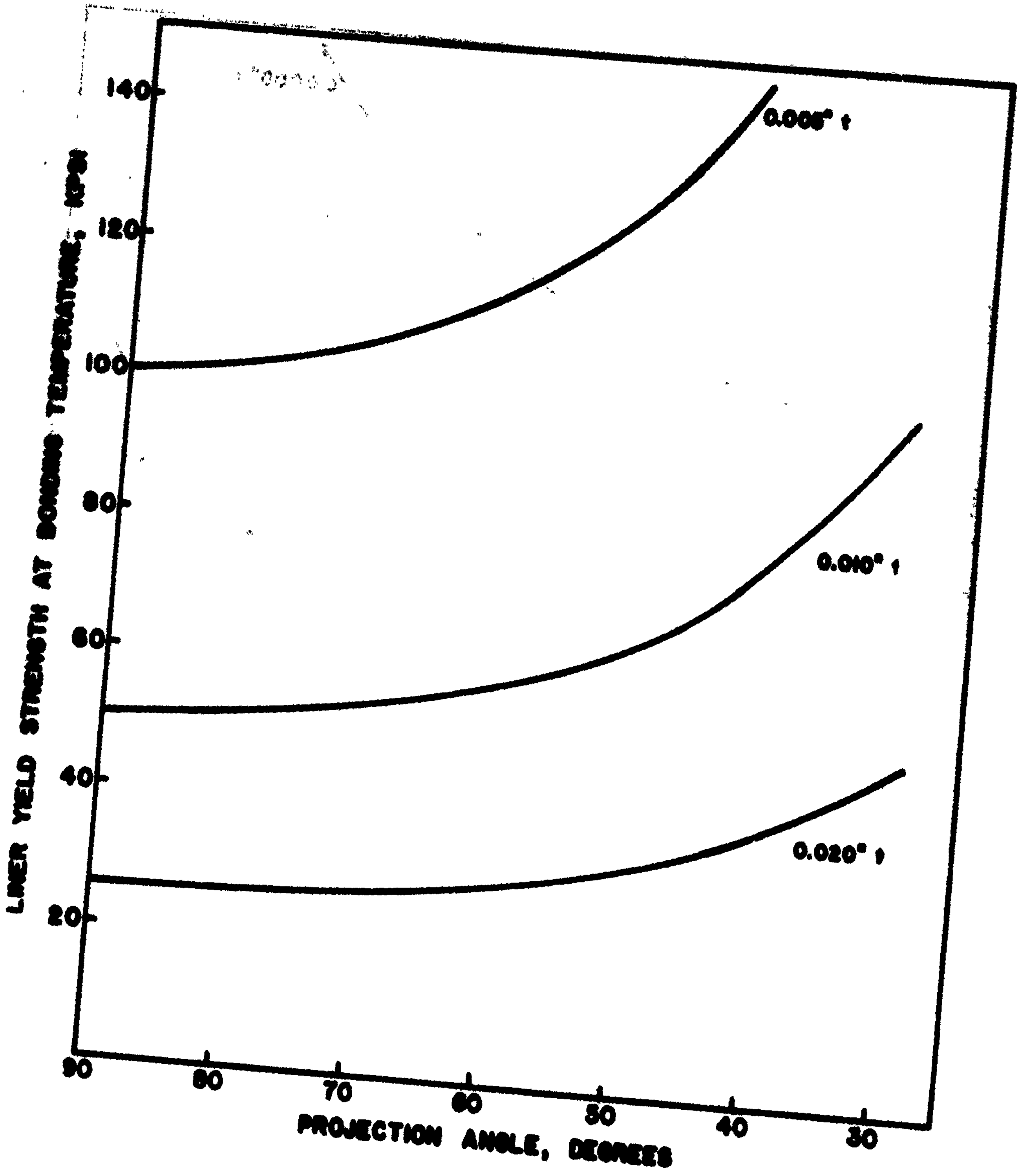


FIGURE 29 Influence of Projection Angle on Conformity to Projection Height of 0.050 Inch and to Various Liner Thicknesses

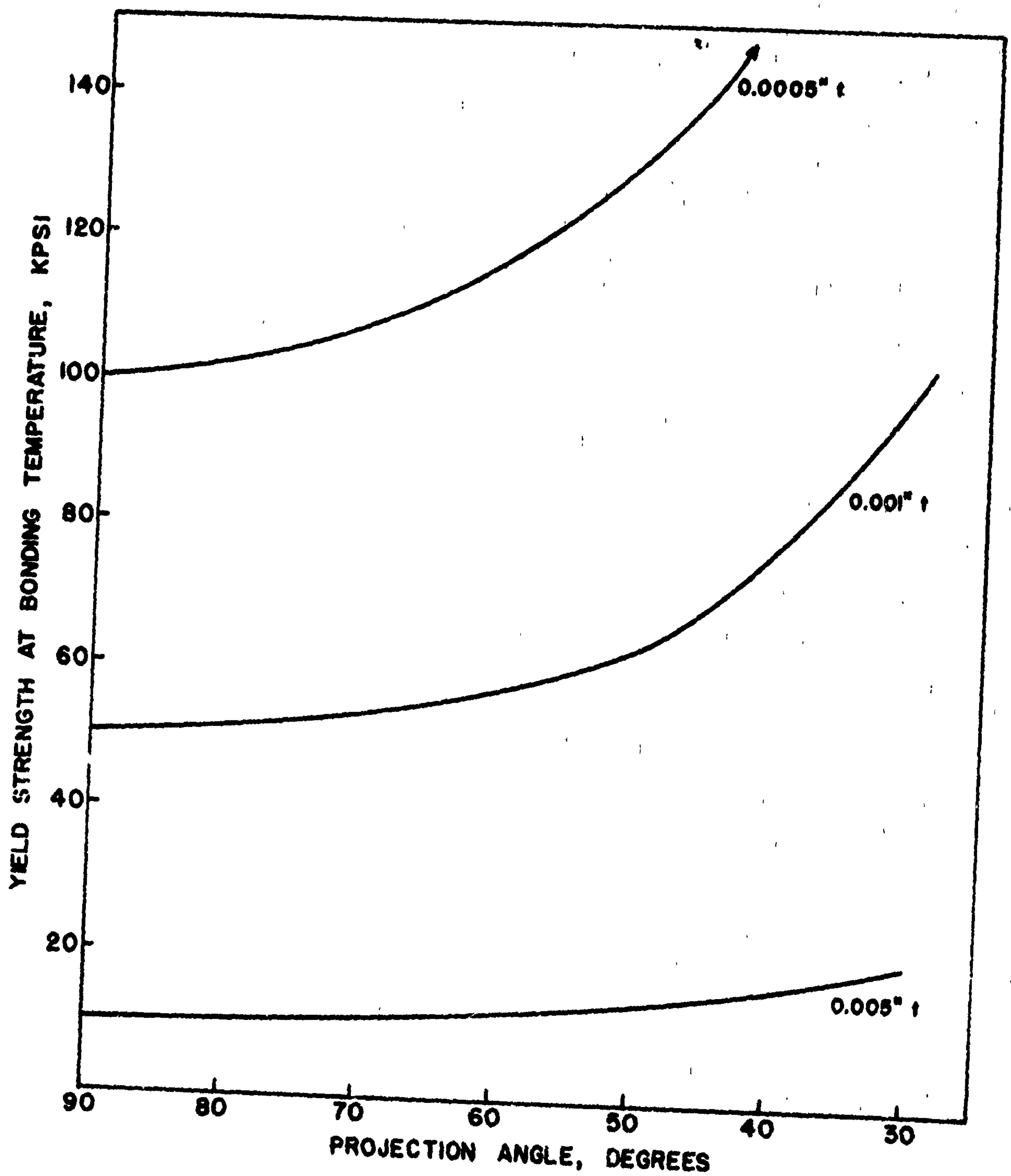


FIGURE 30 Influence of Projection Angle on Conformity to Projection Height of 0.005 Inch and to Various Liner Thicknesses

8. CONCLUSIONS

1. Surface replication of a prerifled barrel projection on a liner cannot be achieved with Ta-10W in liner thicknesses considered desirable with a gas pressure bonding technique.

2. A reasonable prediction can be made that, with a 45° angle projection, a Ta-10W liner of less than 0.001 inch would be necessary at 0.005 inch projection height provided the projection itself could sustain the load.

3. Tests indicate that the steel gun barrel material will become deformed below the bonding temperature required for Ta-10W.

4. Tests with low yield strength liner materials, copper and Monel, did not provide good profile conformity; gaps remain adjacent to projections.

5. Tests with low yield strength liner materials revealed a general relationship that appears to quantitatively predict results accurately enough for practical use.

9. RECOMMENDATIONS

Efforts to join a liner material to a prerifled gun tube by gas pressure bonding techniques should be discontinued. Test results from this program indicate that application of this technique is impractical to obtain liner conformity to rifling profile.